BEFORE THE REGIONAL FORESTER
OF THE SOUTHERN REGION
OF THE UNITED STATES FOREST SERVICE

In Re:	)
Appeal of Decision Notice and FONSI	)
Bledsoe Coal Lease KYES-53865	)
Daniel Boone National Forest	)
Kentucky Heartwood,	)
and Cumberland Chapter of the Sierra Club	)
Appellants	)

Appeal _____

NOTICE OF APPEAL

Pursuant to 36 CFR § 215.14, Kentucky Heartwood and the Cumberland Chapter of the Sierra Club appeal the 2013 decision by Forest Supervisor, Frank R. Beum to approve the Bledsoe Coal Lease, KYES-53865.

The relief sought:

The decision by Forest Supervisor Frank Beum to approve the project be reversed and remanded; a proper EA or EIS be developed that appropriately addresses the environmental impacts connected to approval of the Bledsoe Coal Lease.

The Appellants are:

Kentucky Heartwood, Inc., a forest advocacy group dedicated to the health and well-being of the public forests in the Commonwealth of Kentucky. Kentucky Heartwood submitted comments on the EA.

The Cumberland Chapter of the Sierra Club, the Kentucky chapter of a national, non-profit organization dedicated to exploring, enjoying, and protecting the wild places of the earth; to practicing and promoting the responsible use of the earth's ecosystems and resources; and to educating and enlisting humanity to protect and restore the quality of the natural and human environment; and to use all lawful means to carry out these objectives. The Cumberland Chapter of the Sierra Club submitted comments on the scoping document.

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Respectfully submitted by:

Kentucky Heartwood

By: _____

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DATED: June 15, 2013 Appeal _____

STATEMENT OF REASONS

I. Introduction

This appeal challenges the Bledsoe Coal Lease KYES-53865 Environmental Assessment (EA) prepared for the Bureau of Land Management Southeast States Field Office and the Daniel Boone National Forest, Redbird Ranger District, Leslie County, Kentucky, and Finding of No Significant Impact (FONSI) and Decision Notice (DN) approved and signed by Daniel Boone National Forest Supervisor, Frank Beum, on May 9, 2013. The Appellant asks that the Decision Notice and Finding of No Significant Impact be remanded, and that a proper Environmental Assessment or Environmental Impact Statement be prepared that rightfully and legally considers the environmental impacts resulting from approval and implementation of the Bledsoe Coal Lease.

II. Background

On May 9, 2013, the U.S. Forest Service, Daniel Boone National Forest, approved through a FONSI and DN the Bledsoe Coal Lease. The Bledsoe Coal Lease was proposed following an application from the Bledsoe Coal Company (KYES 053865) and an EA was prepared by Golder Associates, Inc. for the Bureau of Land Management and US Forest Service. Bledsoe Coal Company is a company which has been a persistent violator of mine safety and health laws resulting in numerous accidents and injuries, and at least one death, and has earned several reprimands from the Mine Safety and Health Administration (MSHA), including a rare Pattern of Violations Enforcement action in 2011 for refusal to address serious safety violations at their Abner Branch mine, which was then temporarily shut down by MSHA in 2012 over continued safety violations. After the 2012 shutdown, MSHA put out a press release stating in part:

> "It is clear that, in the case of Abner Branch, a mine already on a pattern of violations, all of MSHA's tools may not be enough. But until that changes, we will use what we have and aggressively enforce the law to ensure men and women who go into a mine at the beginning of a shift can come back out at the end of it."

While outside the scope of this Appeal, we reiterate our concern that the BLM and Forest Service would consider allowing a company such as Bledsoe Coal or related James River Coal subsidiaries, which has acted in flagrant violation of the law resulting in injuries and death, and cost taxpayers through numerous MSHA inspections and actions, to profit from a lease of public, federally-owned coal. While approval of the Bledsoe Coal Lease initiates an open bidding process, Bledsoe Coal's operating of adjacent facilities and application for the lease suggests that they, or a related James River Coal subsidiary, will ultimately receive and profit from the lease and the resulting pollution.

According to the EA, this lease includes the underground mining of 174.4 acres of federally owned coal reserves with 455,080 metric tons of recoverable coal. Based on the volume of coal to be extracted, Appellants estimate that 1,301,528.8 metric tons of CO_2 will be emitted as a clearly connected, indirect effect of the coal lease (based on a U.S. Energy Information Administration provided ratio of 1 ton of coal to 2.86 tons of CO_2). This is roughly equivalent to the carbon emissions of adding just over 85,000 cars to U.S. highways over the projected 3 years of the lease (based on EPA estimates of 5.1 metric tons CO_2 per year per vehicle). In the EA, the BLM and Forest Service wrongfully and illegally failed to analyze and consider the reasonably foreseeable and significant, indirect environmental impacts associated with coal combustion and coal combustion waste generated as a direct result of approving of the Bledsoe Coal Lease. The agencies relied on a suite of arguments that fail the test of reason, as we demonstrate below. Furthermore, the agencies made arbitrary and capricious claims regarding Need for the project and purported economic benefits, refusing to consider multiple sources offering

economic analyses and data that contradict the Forest Service and BLM's desired and predetermined outcome for the analysis. As such, the agencies failed in their legal obligations under NEPA and could not have made an informed decision resulting in a Finding of No Significant Impact (FONSI) or Decision Notice (DN).

As discussed in our comments on the EA (incorporated by reference), coal combustion is widely recognized as a leading source of several serious pollutants affecting the human and non-human environment, including NO_x, SO_x, Mercury, O_3, and particulates, and is a leading contributor of CO_2 and attendant climate change. Coal ash is recognized as having high concentrations of arsenic, lead, mercury, cadmium, chromium, and selenium, all of which can have significant human health effects, including cancer and neurological damage. The EPA has documented that the above-listed heavy metals and other toxicants can and do escape from coal ash disposal sites, and have confirmed and measured toxic leaching into water supplies and documented human exposure from contaminated drinking water, eating contaminated fish, and breathing "fugitive dust."

We argue that the Purpose and Need for the Bledsoe Coal Lease is biased, that the analysis is arbitrary and capricious, that end-uses and environmental impacts of the extracted coal are "reasonably foreseeable," and as such "indirect effects" under NEPA, and that the BLM and Forest Service violated the law by failing to analyze, disclose, and consider these effects in the Bledsoe Coal Lease EA.

III. The Identified Purpose and Need for the Project are Arbitrary and Capricious

According to the EA, the Need (EA-1.3) for the project "is to assist in addressing the national need for coal." However, the EA fails to consider whether there actually is a national need for coal that ought to be met through providing the publicly-owned coal resources in the Bledsoe Coal Lease to the James River Coal Company or its subsidiaries.

Nowhere does the EA address the well-documented fact that demand for coal, and

Appalachian coal in particular, has dramatically fallen in recent years. Furthermore, according to James River Coal, the parent company of Bledsoe Coal and Shamrock Coal, the Bledsoe complex has 56 million tons of "Probable and Proven" reserves available to the company, and has an estimated reserve life of 50 years at 2012 extraction levels (2012 James River Coal Annual Report). As such, the coal in the Bledsoe Coal Lease accounts for merely 0.9% of the coal reserves in this complex that are accessible to the applicant, meaning that the coal offered in the lease is not "needed," only wanted. There is a difference.

Simply saying that there is a need to be met while failing to address factual, contrary information is arbitrary and capricious and a violation of NEPA.

IV. The Forest Service's Analysis is Fundamentally Arbitrary and Capricious

The analysis is, at heart, arbitrary and capricious, and suggesting of a predetermined outcome. Ostensibly positive economic impacts (which we address further below) are treated in the analysis as additive. Specifically, the BLM and Forest Service go to great length in the EA to show the economic importance of mining the coal in the Bledsoe Coal Lease as an economically additive endeavor. Mining the coal is portrayed as increasing the available amount of coal, increasing local income, and increasing corporate and government revenue. However, the environmental impacts associated with mining the coal are treated as non-additive; that is, the Forest Service asserts that there will be no changes locally or regionally in the amount of coal being processed, transported, burned, or disposed of, and therefore the environmental effects of such activities are not significant.

In its Consideration of Comments, the Forest Service responds to this point made in our comments on the EA merely with:

> "This comment reflects a disagreement with the stated purpose of and need for the proposed action. While the production rates and volumes would not change, the mining of the federal coal in addition to nearby private leases would extend the

life of the facilities by up to three years." (Consideration 1-6)

It is illogical at best to assert that mining and utilizing the coal reserves in the Bledsoe Coal Lease will add dollars but not pollutants or other environmental impacts. The *only* way that the coal in the Bledsoe Coal Lease translates to economic activity is through its mining, processing, transportation, sale, utilization, and disposal. The agencies cannot have it both ways.

Even without the above fantasy of simultaneously additive positive and non-additive negative effects of extracting the coal in this lease, it is an unreasonable assumption that extracting, processing, transporting, burning, and disposing of the coal from this lease will have no environmental effects because it only maintains the status quo. This reasoning is fatally flawed because it assumes that coal is an unlimited and/or renewable resource. This is simply not true. Coal deposits are finite and will not be naturally replenished on any meaningful timescale. Keeping these particular coal deposits in the ground will ensure that they do not contribute to global climate change, heavy metal pollution, acid rain, or other detrimental environmental effects whether by being combusted domestically or exported for sale on the international market. As is stated in the EA, denial of this permit will result in the coal being economically unavailable in the future. If the permit is denied, this specific coal will not be extracted, its carbon not released into the atmosphere, its mercury not deposited in streams to bioaccumulate, nor its particulates inhaled by at-risk populations near power plants who are already prone to asthma and death from poor air quality.

The analysis is further flawed in the agencies' arbitrary and biased treatment of economic data. In response to the lengthy economic section in the EA promoting ostensible economic benefits stemming from implementing the project and approving the lease, exemplified by the emphatic statement that "Mining of this coal would provide economic returns to the national, state, and local economies. (EA−1.2)", appellants submitted in our comments on the EA a study by the Mountain Association for Community Economic Development (Exhibit 1) that found, even in the

absence of well-documented health-related economic impacts, the budgetary impact of the coal industry on the state of Kentucky was a conservative net loss of $115,000,000 per year. The Forest Service refused to consider these negative financial impacts by saying:

> "The *Mountain Association for Community Economic Development* study includes costs calculated on a state-wide basis, in general for the coal industry, but does not provide meaningful data for evaluating costs relative to an individual operation." (Consideration 1-7)

However, the Forest Service freely used other studies and data in the EA and administrative record that are similarly or more broad in their scope to justify the coal lease. For example, in Consideration 1-7 in the Consideration of Comments, the Forest Service cites The US Energy Information Administration Short-Term Energy Outlook report US EIA (2013) to suggest that coal consumption is anticipated to increase marginally in the near future. The agency similarly lists in the project record the US EIA report "Coal News and Markets. Spot Coal Price (October 9, 2012)" which offers economic data by region, for which the most specific data relative to the Bledsoe Coal Lease are for "Central Appalachia," a much more general area and analysis than found in the MACED study rejected by the Forest Service. How are nation- and region-wide economic reports specific enough to be used as economic justification for the Bledsoe Coal Lease, while a state-wide economic report is considered too broad to consider?

Similarly, in response to our comments that the Forest Service consider monetized health impacts as discussed in Levy et al. (2009) (Exhibit 2), the Forest Service refused consideration by stating:

> "Concerning the Levy study, as stated in the response to Comment 1-1, because the types and location of specific facilities where the coal might be burned is not reasonably foreseeable, estimates of the effects of emissions from such unknown uses are speculative, and are outside of the scope of this EA." (Consideration 1-7)

As we demonstrate in exhaustive detail below, the Forest Service's use of "not reasonably foreseeable" and "speculative" are incorrect in fact and law, and not sufficient to ignore real data that contradict the Forest Service's clear bias toward approving the coal lease.

Nor does the Forest Service acknowledge the Epstein et al. (2011) (Exhibit 3) study discussed in Appellants comments on the EA, Full Cost Accounting for the Life Cycle of Coal, where the authors state:

> "We estimate that the life cycle effects of coal and the waste stream generated are costing the U.S. public a third to over one-half of a trillion dollars annually."

While only available after publication of the DN and FONSI, we point to the Interagency Working Group on Social Cost of Carbon Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis - Under Executive Order 12866 (Exhibit 4), which in May, 2013 substantially revised upward its estimates of the realized social costs of carbon outputs. According to the Executive Summary:

> "Under Executive Order 12866, agencies are required, to the extent permitted by law, 'to assess both the costs and the benefits of the intended regulation and, recognizing that some costs and benefits are difficult to quantify, propose or adopt a regulation only upon a reasoned determination that the benefits of the intended regulation justify its costs.' The purpose of the "social cost of carbon" (SCC) estimates presented here is to allow agencies to incorporate the social benefits of reducing carbon dioxide (CO2) emissions into cost-benefit analyses of regulatory actions that impact cumulative global emissions. The SCC is an estimate of the monetized damages associated with an incremental increase in carbon emissions in a given year. It is intended to include (but is not limited to) changes in net agricultural productivity, human health, property damages from increased flood

> risk, and the value of ecosystem services due to climate change."

This government report provides economic costs per ton of carbon to be used by regulatory authorities in making cost-benefit decisions. The report states:

> "The four 2020 SCC estimates reported in the 2010 TSD were $7, $26, $42 and $81 (2007$). The corresponding four updated SCC estimates for 2020 are $12, $43, $65, and $129 (2007$)."

Based on this assessment, the monetized social costs of CO_2 from approving the Bledsoe Coal Lease range from $15.6 million to $167.9 million. While a wide range, the Forest Service made no effort to consider any negative economic costs associated with the project, including those from authoritative studies and the federal government.

Federal agencies are allowed to exercise considerable discretion in deciding what sources of information are most appropriate for a given analysis. However, federal agencies are *not* allowed to selectively pick data supporting one predetermined position and outcome while ignoring other authoritative, contradicting data on spurious grounds as the Forest Service has done. The BLM and Forest Service have acted illegally by arbitrarily and capriciously refusing to consider real and negative economic impacts associated with approval of the Bledsoe Coal Lease, limiting the analysis to information that fits the agencies' desired and pre-determined result of showing erroneously that approval of the Bledsoe Coal Lease will result in a net positive economic impact.

V. The Scope of Analysis and Consideration of Indirect Effects are too Narrow, and Ignore Significant Reasonably Foreseeable Impacts

Providing accurate and relevant information to both the decisionmaker and the public in the interest of arriving at an informed decision is at the heart of NEPA. The Supreme Court stated in Robertson v. Methow Valley Citizens Council, 490 U.S. 332, 109 S. Ct. 1835, 104 L. Ed. 2d 351 (1989) that NEPA:

> "ensures that the agency, in reaching its decision, will have available, and will carefully consider, detailed information concerning significant environmental impacts; it also guarantees that the relevant information will be made available to the larger audience that may also play a role in both the decisionmaking process and the implementation of that decision."

Courts have made clear that NEPA does not require an exhaustive exploration of every possible impact or outcome of a proposed action, and have given considerable deference to federal agencies in defining the parameters for analysis. However, the agency does not have complete discretion to ignore environmental effects that are "reasonably foreseeable," and that flow from the proposed action, regardless of proximity to the project area or time of implementation.

According to 40 CFR § 1508.8, "effects" is defined to "include: (a) Direct effects, which are caused by the action and occur at the same time and place," and "(b) Indirect effects, which are caused by the action and are ***later in time or farther removed in distance, but are still reasonably foreseeable***." (emphasis added).

In its Consideration of Comments, the Forest Service states that "Coal combustion impacts are not included in this cumulative analysis because these are potential impacts that are speculative, not reasonably foreseeable, and there is not a 'reasonably close causal relationship' to the proposed action, and as such do not need to be analyzed." We argue vigorously that the Forest Service has erred in this consideration and interpretation. In fact, the Forest Service's position is directly contradicted by the approach taken by the Forest Service and other agencies in conducting NEPA review of other coal leases.

Whether or not the Forest Service needs to disclose and consider in an EA or EIS the end-use effects the coal extracted from the Bledsoe Coal Lease hinges, in large part, on whether or not the effects are "reasonably foreseeable," and thus "indirect effects" per 40 C.F.R. § 1508.8.

Mid States Coalition for Progress v. Surface Transportation Board, 345 F.3d 520 (8th Cir. 2003) states:

> NEPA requires that federal agencies consider "any adverse environmental effects" of their "major ... actions," 42 U.S.C. § 4332(C), and the CEQ regulations, which are binding on the agencies, explain that "effects" include both "direct effects" and "indirect effects," 40 C.F.R. § 1508.8. Indirect effects are defined as those that "are caused by the action and are later in time or farther removed in distance, but are still reasonably foreseeable." *Id.* "Indirect effects may include ... effects on air and water and other natural systems, including ecosystems." *Id.* The above language leaves little doubt that the type of effect at issue here, degradation in air quality, is indeed something that must be addressed in an EIS if it is "reasonably foreseeable," *see id.* As in other legal contexts, an environmental effect is "reasonably foreseeable" if it is "sufficiently likely to occur that a person of ordinary prudence would take it into account in reaching a decision."

The last sentence above is from Sierra Club v. Marsh, 976 F.2d 763, 767 (1st Cir.1992), where the court elaborates:

> "As in other legal contexts, the terms "likely" and "foreseeable," as applied to a type of environmental impact, are properly interpreted as meaning that the impact is sufficiently likely to occur that a person of ordinary prudence would take it into account in reaching a decision…That is, a likelihood of occurrence, which gives rise to the duty, is determined from the perspective of the person of ordinary prudence in the position of the decisionmaker at the time the decision is made about what to include in the EIS."

We contend that a "person of ordinary prudence," that is, an average person offering consideration of the issue, would not dissociate coal extraction from coal combustion and its environmental impacts.

In the Consideration of Comments the Forest Service cites a BLM document to explain why the connected end-use of the extracted coal is too speculative to warrant consideration and analysis.

> "The BLM document dated December 14, 2011, "Integrating Climate Change into the NEPA Process", provides guidance and consideration as to how the Bureau of Land Management should address climate change issues during the project-level NEPA process. The last paragraph of page 6 of this BLM document states the following: "The consumption of commodities produced on BLM lands (e.g. coal, oil and gas), would typically not constitute an indirect effect of the proposed action because it is not reasonably foreseeable how those commodities will be used. It is also difficult to discern if the consumption of those or any commodities is actually caused by the BLM's action. For example, how crude oil will be used, whether any or all of the oil will be refined for plastics or other products that will not be burned; the possible mix of ultimate uses with disparate carbon emissions (e.g., auto fuel, bunker oil, diesel, kerosene); and the market forces that may replace lost BLM production with production from other sources are all uncertain. Therefore, the greenhouse gas emissions that may ultimately result from the consumption of products derived from the crude oil generated on BLM lands would not be reasonably foreseeable, and thus would not constitute an indirect effect of a BLM decision to approve the leasing, development, or production of oil in that area." (Response 1-1)

The above guidance offers as example the wide range of uses resulting from the extraction and processing of oil. The uses of coal are much less speculative, and mostly limited to thermal and metallurgical uses (i.e., power plants and steel mills). James River Coal, which operates the Bledsoe complex, reported in their 2012 Annual Report that "We mine, process and sell thermal and metallurgical coal through eight active mining complexes located throughout eastern Kentucky, southern West Virginia and southern Indiana. The majority of our metallurgical coal was obtained in the April 18, 2011 acquisition (the IRP Acquisition) of International Resource Partners LP and its subsidiary companies," reasonably implying that that coal from subsidiaries Bledsoe Coal company

(acquired in 1995) and Shamrock Coal company (acquired in 1999), which currently mine the Bledsoe Complex, submitted the lease proposal, and provided much of the data used in the EA, is primarily thermal coal used in the production of electricity.

This assertion was easily confirmed with an email on June 6, 2013 to James River Coal (attached), which informed Kentucky Heartwood that "Our metallurgical coal comes out of our West Virginia mines" (Beth Cook, Director of Investor Relations, James River Coal Company). Considering Bledsoe Coal and Shamrock Coal, both James River subsidiaries, provided substantial data for the EA, this information, had it been sought, should have been readily available to the Forest Service and BLM when preparing the EA.

Additionally, the EA (EA-104) states "In addition, coal mined in Kentucky has several valuable end uses: electricity generation, heat, and coking coal for iron and steel production." Considering that coal from the Bledsoe complex is, according to James River Coal, not used in coking, it is certainly reasonable to assume for the sake of analysis of environmental impacts that most of the coal mined will be used for generation of electricity. If the agency is confident to use the assumption that the coal mined may be used for electricity generation, heat, and coking for discussion on economic considerations, how is it speculative in environmental considerations?

Given the above, we reassert that a person of "ordinary prudence" would consider it "sufficiently likely to occur" that most or all of the coal in the Bledsoe Coal Lease will be burned for the generation of electricity.

And while the precise identity of the end-use facility for burning the coal, and thus specifics regarding emissions and disposal, may be speculative, the *nature* of the use, and therefore the *nature* of the effect, is not. In Mid States Coalition for Progress v. Surface Transportation Board, 345 F.3d 520 (8th Cir. 2003), the Court states (emphasis orginal):

> "Contrary to DM & E's assertion, when the *nature* of the effect is reasonably

> foreseeable but its *extent* is not, we think that the agency may not simply ignore the effect. The CEQ has devised a specific procedure for "evaluating reasonably foreseeable significant adverse effects on the human environment" when "there is incomplete or unavailable information." 40 C.F.R. § 1502.22. First, "the agency shall always make clear that such information is lacking." Id. Then, "[i]f the information relevant to reasonably foreseeable significant adverse impacts cannot be obtained because the overall costs of obtaining it are exorbitant or the means to obtain it are not known," the agency must include in the environmental impact statement:
>
> (1) A statement that such information is incomplete or unavailable; (2) a statement of the relevance of the incomplete or unavailable information to evaluating reasonably foreseeable significant adverse impacts on the human environment; (3) a summary of existing credible scientific evidence which is relevant to evaluating the reasonably foreseeable significant adverse impacts on the human environment, and (4) the agency's evaluation of such impacts based upon theoretical approaches or research methods generally accepted in the scientific community.
>
> Id. at § 1502.22(b).

The Forest Service and BLM Regularly Analyze Coal Combustion Impacts in the NEPA Review of Coal Leases

Perhaps most notably, the Forest Service's refusal to consider coal combustion impacts associated with this coal lease is directly contrary to the approach taken by the Forest Service and BLM in conducting the NEPA review for other federal coal leases. It is the definition of arbitrary and capricious for an agency to take one position in one case, and the exact opposite position in a directly comparable case.

In the FEIS for the Wright Area coal leases in Wyoming, where the Forest Service was a cooperating agency, BLM and the Forest Service

> “assumed that this coal will be sold to coal users in response to forecasts

> of demand for this coal. Historically these users have been electric utilities in the U.S., although there is potential for sales outside the U.S."

Wright Area FEIS, Volume 4, at 4-137.

The FEIS then projected future greenhouse gas emissions from the combustion of the coal covered by the proposed leases. The FEIS accomplished this by calculating greenhouse gas emissions from the coal mined in the previous year by the mines expected to purchase the proposed coal leases

> "The three WAC applicant mines produced 228.3 million tons of coal in 2008, which represents about 50.5 percent of the coal produced in the Wyoming PRB in 2008. Combustion of those 228.3 million tons of coal to produce electricity produced approximately 378.7 million tonnes of CO2 emissions, or about 5.4 percent of the total estimated anthropogenic CO2 emissions produced in the U.S. in 2008, which was approximately 7,052.6 million tonnes (USDOE 2009c)."

Wright Area FEIS, Volume 4, at 4-139.

The FEIS included a table showing "Estimated Annual CO2 Emissions Produced from Combustion of Coal Produced from WAC LBA Tracts." Wright Area FEIS, Volume 4, at 4-140 (Table 4-39).

The BLM also considered the environmental impacts of coal combustion in its EA for the Elk Creek East Tract Coal Lease. The Forest Service later relied on that EA in its decision to consent to the coal lease, which sits under the Grand Mesa-Uncompahgre-Gunnison National Forest. In the Elk Creek East EA, in a section titled "Combustion," BLM noted that

> "Historically, the coal mined in Colorado has been used as one of the sources of fuel to generate electricity in power plants located throughout

> the U.S., and shipped overseas. The mines in Colorado have sold, and are expected to sell, coal into the open coal market. The mine's ability to sell coal in this market is determined by the annual production rates at that mine. Coal sales are made on short term contracts or sold on a spot market. This market is very dynamic and competitive. During the coal lease application process, it is uncertain and speculative to predict who might purchase future Colorado coal, how it would be used, and where the coal might be transported to. Moreover, the restrictions and control measures vary by the location in which the coal is burned. . . . According to the U.S. Energy Information Administration (2009), nearly 94 percent of all coal consumed in the U.S. during 2009 was used in the generation of electric power. Because of this, it can reasonably be assumed that the coal will be shipped to a coal-fired power plant. It would be possible to provide a quantification of GHG emissions associated with the burning of the mined coal at a specific facility; however, the types and location of the facilities the coal might be processed in is speculative and not foreseeable."

Elk Creek East EA at 18.

Nevertheless, BLM went on to produce its best estimate of the greenhouse gas emissions that would result from combustion of the coal contained in the lease

> "Even though the BLM cannot reasonably predict the destination of where the coal will be burned, it is still possible to do emissions calculation if the number of tons of coal produced year from a mine, and the heat content of that coal in BTUs per ton, is known. This information is known for the proposed lease tract. However since the type of facility the coal might be processed in (i.e., the control efficiency of the facility) is speculative; calculations were made using average numbers in U.S. facilities. Therefore the emissions calculation does not represent an accurate estimate of potential GHG emissions from this specific project. That said,

> assuming the Proposed Action Alternative would generate 3.96 million tons of high-quality low-sulfur super-compliant bituminous coal per year, with an average heat content of 24.2 million British thermal units (BTUs) per ton, nearly 9.6 million metric tons of carbon dioxide equivalent (CO2e) would be emitted. This amount represents nearly 8 percent of all CO2e emissions in Colorado during 2007, nearly 0.14 percent of all CO2e emissions in the U.S. during 2007, and nearly 0.04 percent of global CO2 emissions during 2007 (CAIT-US 2011). These calculations are based upon default emission factors for stationary combustion in the Energy Industries (IPCC 2006), assuming no other use of the coal and complete total combustion, and therefore represent a conservative overestimate of potential GHG emissions."

Elk Creek East EA at 20.

The U.S. Department of Interior, Interior Board of Land Appeals (IBLA) specifically pointed to that combustion impact assessment for the Elk Creek East tract in its Decision to uphold the EA, Dated March 27, 2012. The IBLA specifically noted that:

> "In order to address the potential environmental impacts of leasing 786 acres of Federal lands in the ECET, BLM prepared the 68-page EA. Under the Proposed Action Alternative, mining the coal was considered to be the logical consequence of leasing the coal. For purposes of assessing environmental impacts, BLM assumed that Oxbow would be the successful bidder for the lease, thus resulting in development of the coal in conjunction with its Mine. *See* EA at 2. The EA considered the individual and cumulative impacts not only of mining the coal, but also of burning the coal in dispersed coal-fired electrical power plants in the United States. In the EA, BLM also considered a no-action alternative."

There is absolutely no reason why the Forest Service and BLM could not have taken the same approach as the Wright Area FEIS and Elk Creek East EA and estimated the

greenhouse gas emissions from combustion of the coal in the Bledsoe Coal Lease. Accordingly, there is absolutely no support for the Forest Service's assertion that the impacts of that coal combustion are "speculative, not reasonably foreseeable, (with no) 'reasonably close causal relationship' to the proposed action." That assertion is arbitrary and capricious, and cannot be allowed to stand.

The environmental and health effects of coal combustion and waste disposal have been widely studied and publicized. The Forest Service's contention that these impacts cannot be analyzed and discussed in a meaningful manner without knowing which particular facilities the coal will go to is an insufficient excuse for the agencies' failure to disclose the impacts in the EA.

"Reasonably Close Causal Relationship"

The Forest Service also contends that there is no "reasonably close causal relationship" between approval of the Bledsoe Coal Lease and combustion of the mined coal, and therefore the pollution associated with burning and disposing of the coal does not need to be considered in the EA. We disagree as a matter of fact and law.

SAN LUIS OBISPO PEACE v. Nuclear Regulatory Commission, 449 F. 3d 1016 (8th Cir. 2005) holds that whether there is a "reasonably close causal relationship" hinges on whether or not the consequences in question are "remote and highly speculative." As demonstrated above, the relationship between the approval of this project, the act of burning the coal, and the pollution associated with coal combustion and waste disposal are direct and obvious and in no way "remote and highly speculative." Cases where courts have rejected claims of there being a "reasonably close causal relationship" between an a federal action and a potential environmental effect typically relate to the remoteness of risk or significant improbability that a particular consequence could flow from the proposed action. It is not "remote and highly speculative" that the coal from the Bledsoe Coal Lease will be combusted and its waste products disposed of. In fact, it is a near certainty that the coal from this project will be burned and emit pollutants.

As the above clearly shows, the Forest Service's contention that "Coal combustion impacts… are potential impacts that are speculative, not reasonably foreseeable, and there is not a 'reasonably close causal relationship' to the proposed action" is wrong in both fact and law. In simple terms, if the coal from this lease stays in the ground it will not be burned and not contribute to the environmental impacts associated with coal combustion and coal combustion waste. If the lease is granted then it will. Therefore, the Forest Service's reasoning is improper and the EA is legally deficient.

CEQ and Forest Service Guidance

As further reasoning for avoiding consideration of coal combustion impacts, the Forest Service cites in its Consideration of Comments a Council on Environmental Quality (CEQ) letter dated February 18, 2010; "Draft NEPA Guidance on Consideration of the Effects of Climate Change and Greenhouse Gas Emissions," quoting:

> "Under this proposed guidance, agencies should use the scoping process to set reasonable spatial and temporal boundaries for this assessment and focus on aspects of climate change that may lead to changes in the impacts, sustainability, vulnerability and design of the proposed action and alternative courses of action. At the same time, agencies should recognize the scientific limits of their ability to accurately predict climate change effects, especially of a short-term nature, and not devote effort to analyzing wholly speculative effects."

Nowhere in this statement does is indicate or imply that the Forest Service should not consider the impacts of burning fossil fuels extracted from national forest lands. In fact, it recommends "not devot(ing) effort to analyzing wholly speculative effects," implying that effects that are *not* speculative, but are indeed reasonably foreseeable, ought to be considered.

The Forest Service continues in the Consideration of Comments by citing a Forest

Service letter dated January 16, 2009, "Considering Climate Change in Land Management and Project Planning," and the included attachment, "Climate Change Consideration in Project Level NEPA Analysis," dated January 13, 2009, which provides guidance on how to consider climate change in project-level NEPA analysis and documentation, quoting:

> "An analysis of GHG emissions and carbon cycles is not always appropriate for every NEPA document. As with any environmental impact, GHG emissions and carbon cycling should be considered in proportion to the nature and scope of the Federal action in question and its potential to either affect emissions or to be affected by climate change impacts. As with any environmental analysis, the scope of the effects needs to be established in timing and geography relative to the scope of the actions being considered in the alternatives."

Again, this guidance neither states nor implies that the Forest Service ought *not* to consider the impacts of burning fossil fuels extracted from the national forest. It suggests such consideration is, at times, appropriate, and that consideration of GHG emissions should relate to the "nature and scope of the Federal action." Burning fossil fuels from the national forest is precisely the type of Federal action where such analysis is appropriate. We cannot think of any federal action on the national forest lands that would be more appropriate for such analysis.

Furthermore, neither document suggests that other indirect environmental effects, including those from NO_x, SO_x, Mercury, O_3 and particulates from coal combustion, nor arsenic, lead, mercury, cadmium, chromium, and selenium from coal ash waste, or any other effects, ought not be considered.

Other Regulatory Authorities

The Forest Service also defends its failure to analyze the indirect effects of mining the coal in the Bledsoe Coal Lease on the grounds that combustion, and presumably

waste disposal, are adequately addressed by other regulations and permitting authorities. The Consideration of Comments states:

> "It is also likely that impacts from coal-burning facilities have been appropriately analyzed by the applicable permitting authority, such that any local or regional impacts from the combustion facilities would not exceed those already authorized." (Response 1-1)

This is not a reasonable assumption on multiple grounds. Firstly, with regards to climate impacts, GHGs are currently unregulated on existing powerplants, therefore the above assumption does not hold in the slightest. With regards to other pollutants regulated under the Clean Air Act (CAA), it must be pointed out that the National Ambient Air Quality Standards (NAAQS) are essentially policy-based standards that result as a compromise between multiple factors and interests, including, but not limited to, the best available science as relates to protecting human health. For example, EPA has long agreed that there is a linear relationship between ambient levels of $PM_{2.5}$ and death, but the agency does not set NAAQS for $PM_{2.5}$ at zero, even though doing so would save lives, because this would effectively shut down the US economy. Therefore, equating an assumption that permitted facilities will not exceed current NAAQS with an assumption of no environmental impact is erroneous. This is even more so as it can take years, even decades, for new science to translate to updates to the CAA and NAAQS. In this case, BLM and Forest Service violated NEPA by failing to take a hard look at the impacts based on current science, instead relying on false assumptions about regulatory systems outside their purview.

In Shell Gulf of Mexico, Inc. & Shell Offshore, Inc. (OCS Appeal Nos. 10-01 through 10-04), decided December 30, 2010, the U.S. EPA Environmental Appeals Board ruled that it was improper for the Region to rely solely on existing NAAQS for NO_2 as related to environmental justice considerations because EPA was in the process of developing new, more stringent standards. Though the new standards had yet to be finalized at the time of the Region's decision, the Board rejected the Region's reliance on the existing

standards because EPA had already concluded, based on current science, that the existing standards were not sufficient to protect human health – even thought new standards had yet to be finalized.

In this case, we point to US EPAs Integrated Science Assessment for Ozone (Exhibit 5), which shows that the current standard, set in 2008, is not sufficient to protect human and environmental health. Ozone is among the suite of pollutants emitted from coal-burning facilities that have a disproportionate effect on at-risk communities near coal-fired powerplants. Approving the permit for the Bledsoe Coal Lease is likely to result in coal combustion and the production of O_3.

With regards to coal ash, currently no federal regulations oversee coal ash disposal, with EPA having repeatedly delayed new regulations. Current regulations, such as they are, are set by states, inconsistent, and frequently inadequate in protecting human and environmental health. In 2010, the EPA published a risk assessment (Exhibit 6) that found extremely high risks to human health and the environment from the disposal of coal ash in waste ponds and landfills. EPA found that the cancer risk from coal ash is 2,000 times greater than the regulatory goal.

Kentucky has 43 coal ash ponds at 17 sites. Ten of Kentucky's coal ash ponds and landfills are unlined, eight have no leachate collection systems, and five have no groundwater monitoring systems. EPA has designated eight ponds in Kentucky as "high hazard," six ponds as "significant hazard," with nineteen not rated as of 2009. (Exhibit 7)

In nearby Ohio, regulations fail to require all new and existing coal ash ponds and landfills to monitor groundwater or install composite liners; the state does not prohibit coal ash ponds from being constructed in the water table; nor does the state require ponds or landfills to have financial assurance that would ensure funds for a cleanup in the event of a spill.

And in Harriman, Tennessee on December 22, 2008, a coal ash dam at the Tennessee

Valley Authority (TVA) Kingston Fossil Plant broke, releasing 1.1 billion gallons of coal ash into the Emory and Clinch Rivers, destroying three homes and damaging a dozen others.

Clearly, the assumption on the part of the Forest Service that coal ash waste is adequately regulated with environmental impacts duly considered by an authoritative body is erroneous, and in no way a reasonable assumption that lawfully exempts the agency from consideration of the environmental effects of coal ash stemming resulting from combustion of the coal in the proposed Bledsoe Coal Lease.

TABLE OF EXHIBITS

Exhibit 1: Konty, Melissa F. and Bailey, J. 2009. The Impact of Coal on the Kentucky State Budget. Mountain Association for Community Economic Development, Berea, KY.

Exhibit 2: Levy, Jonathan I., Baxter, L.K., and Schwartz, J. 2009. Uncertainty and Variability in Health-Related Damages from Coal-Fired Power Plants in the United States. Risk Analysis 29(7).

Exhibit 3: Epstein, Paul R., Buonocore, J.J., Eckerle, K., Hendryx, M., Stout, B.M. III, Heinberg, R., Clapp, R.W., May, B., Reinhart, N.L., Ahern, M.M., Doshi, S.K., and Glustrom, L. 2011. Full cost accounting for the life cycle of coal. Annals of the New York Academy of Sciences, 1219(2011), 73-98.

Exhibit 4: Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866. Interagency Working Group on Social Cost of Carbon, United States Government. May 2013.

Exhibit 5: US EPA Integrated Science Assessment for Ozone, 1251pp., incorporated by reference; http://www.epa.gov/ncea/isa/ozone.htm (accessed June 11, 2013)

Exhibit 6: Evans, Becher & Lee, "STATE OF FAILURE: How States Fail to Protect Our Health and Drinking Water from Toxic Coal Ash" at 3 (Earthjustice and Appalachian Mountain Advocates 2011).

Exhibit 7: Kentucky Coal Ash Fact Sheet. EarthJustice.

Exhibit 8: Wright Area Coal Lease FEIS excerpt.

Exhibit 9: Elk Creek East Tract Coal Lease EA excerpt.

Exhibit 10: Human and Ecological Risk Assessment of Coal Combustion Wastes. Draft, April 2010. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Office of Resource Conservation and Recovery. Regulation Identifier Number (RIN) 2050-AE81.

EXHIBITS

The Impact of Coal on the Kentucky State Budget

Visit www.maced.org/coal for the full report and more information on the economy of coal in Kentucky.

MACED
Mountain Association for Community Economic Development

The Impact of Coal on the Kentucky State Budget

by Melissa Fry Konty, Ph.D. and Jason Bailey

June 25, 2009

We extend special thanks to all those who reviewed and commented on earlier drafts of *The Impact of Coal on the Kentucky State Budget* and *The Economics of Coal in Kentucky*. We received a tremendous amount of feedback that no doubt improved the quality of our work.

We appreciate the hard work of several student interns who helped bring the report and support pieces to completion: Thupten Dhondup, Jenna Lowe, Kristin Tracz and Dilshod Yusupov.

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For over 30 years, MACED has worked to improve the quality of life in eastern Kentucky and Central Appalachia by creating economic opportunity, strengthening democracy and supporting the sustainable use of natural resources. MACED seeks to transform the lives of people and places in need through sustainable development. We employ three main strategies toward this goal: 1) Community Investment — Investing capital and capacity-building technical assistance in people and enterprises to create economic opportunities, protect natural and cultural assets and provide critical services; 2) Demonstration Initiatives — Developing new approaches to old problems and testing them out on the ground; and 3) Research for Policy Change — Conducting research around policy opportunities and barriers that results in better development practice and opportunities for people who need them.

The Impact of Coal on the Kentucky State Budget

Executive Summary

Rapid and dramatic changes in the world's approach to energy have major implications for Kentucky and its coal industry. Concerns about climate change are driving policy that favors cleaner energy sources and increases the price of fossil fuels. The transition to sustainable forms of energy, already underway, will become a major economic driver, as states move aggressively to develop, produce and install the energy technologies of the future. Long reliant on coal for jobs and electricity, Kentucky faces major challenges and difficult choices in the coming years.

These energy challenges come in the midst of Kentucky's state fiscal crisis and sluggish economic performance. The gap between Kentucky's revenues and expenditures makes it increasingly difficult to sustain existing public services. A recent University of Kentucky report notes that Kentucky ranks 44th among states in per capita income, just as in 1970, while other southern states like North Carolina and Georgia have out-performed the Commonwealth in recent years.[1] Eastern Kentucky still includes 20 of the 100 poorest counties in the United States measured by median household income.[2]

In this critical energy, fiscal and economic context, it is increasingly important for Kentuckians to understand the role and impact of coal in our state. Coal provides economic benefits including jobs, low electricity rates and tax revenue. But the coal industry also imposes a number of costs ranging from regulatory and public infrastructure expenses to environmental and health impacts.

Revenues	
Industry-generated	$303,172,748
Generated from direct employment	83,040,392
Generated from indirect employment	141,509,362
Total Revenues	**$527,722,502**
Tax Expenditures (Foregone Revenues)	
Off-budget items (tax expenditures) specific to coal	(84,753,280)
On-Budget Expenditures	
On-budget items supporting coal	(270,467,828)
Support for direct employment	(73,140,605)
Support for indirect employment	(214,192,262)
Total Expenditures	**($642,553,975)**
Net Impact	**–$114,831,474**

Figure 1: Fiscal Impact Summary

Coal and the Budget

The Impact of Coal on the Kentucky State Budget tells one aspect of the story of coal's costs and benefits. The report provides an analysis of the industry's fiscal impact by estimating the tax revenues generated by coal and the state expenditures associated with supporting the industry. **We estimate for Fiscal Year 2006 Kentucky provided a net subsidy of nearly $115 million to the coal industry (see Figure 1).**

Coal is responsible for an estimated $528 million in state revenues and $643 million in state expenditures. The $528 million in revenues includes $224 million from the coal severance tax and revenues from the corporate income, individual income, sales, property (including unmined minerals) and transportation taxes as well as permit fees. The $643 million in estimated expenditures includes $239 million to address the industry's impact on the coal haul road system as well as expenditures to regulate the environmental and health and safety impacts of coal, support coal worker training, conduct research and development for the coal industry, promote education about coal in the public schools and support the residents directly and indirectly employed by coal. Total costs also include $85 million in tax expenditures designed to subsidize the mining and burning of coal.

The Impact of Coal on the Kentucky State Budget examines coal-related state revenues and expenditures in three parts.

1. **Industry-generated revenues and expenditures.** A review of coal industry-generated revenues to the state and expenditures from the state suggests that the industry actually costs more than it brings to the state. Using state budget and other official state agency data, we estimate the coal industry generated revenues of $303 million for Fiscal Year (FY) 2006. In the same year, on-budget spending to support coal industry activities totals more than $270 million and off-budget tax expenditures add $85 million to the coal industry's bill for a total of more than $355 million. The net direct impact of the industry on the state budget for FY 2006 is an estimated –$52 million.

2. **Revenues and expenditures attributable to direct employment by the industry.** State data sources suggest that FY 2006 revenues attributable to direct employment in coal total $83 million while coal employees' share of state expenditures totals $73 million. The net impact of direct employment in coal on the state budget for FY 2006 is $10 million.

3. **Revenues and expenditures related to indirect employment attributable to the coal industry.** Based on public data and the use of economic impact multipliers, revenues generated by the employment of Kentuckians in supply industries and in sectors that serve those employed by coal total $142 million for FY 2006. State spending to support those whose employment is indirectly attributable to coal totals $214 million. The net impact of indirect employment on the Kentucky state budget is –$73 million.

These figures cover only a portion of the full costs of the coal industry to the state. We do not include the many externalized costs imposed by coal including healthcare, lost productivity resulting from injury and health impacts, water treatment from siltation caused by surface mining, water infrastructure to replace damaged wells, limited development potential due to poor air quality, and social spending associated with declines in coal employment and related economic hardships of coalfield communities. Some of these externalities impose additional costs directly to the state budget while others are borne by communities that mine and burn coal and by those outside the region. The report relies on 2006 figures and does not include the significantly expanded subsidies for advanced coal enabled by House Bill 1 of the 2007 special session of the Kentucky General Assembly.

Assessing the fiscal impact of an entire industry, especially one that is tied to natural resources and that has been a part of our economic and policy structure for so long, is methodologically difficult. The task requires that we rely on numerous assumptions and estimates. However, the approach used here improves upon unsubstantiated speculation of the industry's impact and assessments that only focus on coal's benefits.

Economic Context

The economic and energy contexts for the coal industry are changing. Coal employment continues its long historic decline due to ongoing mechanization of the industry (see Figure 2). In 2008, coal mining accounted for only one percent of Kentucky employment (see Figure 3). Even in the eastern Kentucky counties with the highest share of jobs in coal, mining jobs range from three to 23 percent of the employment base, although coal's high wages make it a larger share of county income. These counties, however, face significant long-term unemployment and poverty rates as high as 37 percent.

Kentucky coal struggles to remain competitive with western coal due to higher production costs. Debate continues over how many years of economically recoverable coal remain in Kentucky, but official sources project a significant decline in production as easy-to-mine coal is depleted. In the future, coal faces additional challenges as aging coal-fired power plants are retired and new laws on carbon emissions raise the price of coal relative to cleaner alternatives. Industry representatives and supporters embrace the potential for new technologies like Carbon Capture and Sequestration to solidify a future for coal. But these technologies face high costs and significant risk and uncertainty, and are already utilizing large public subsidies.

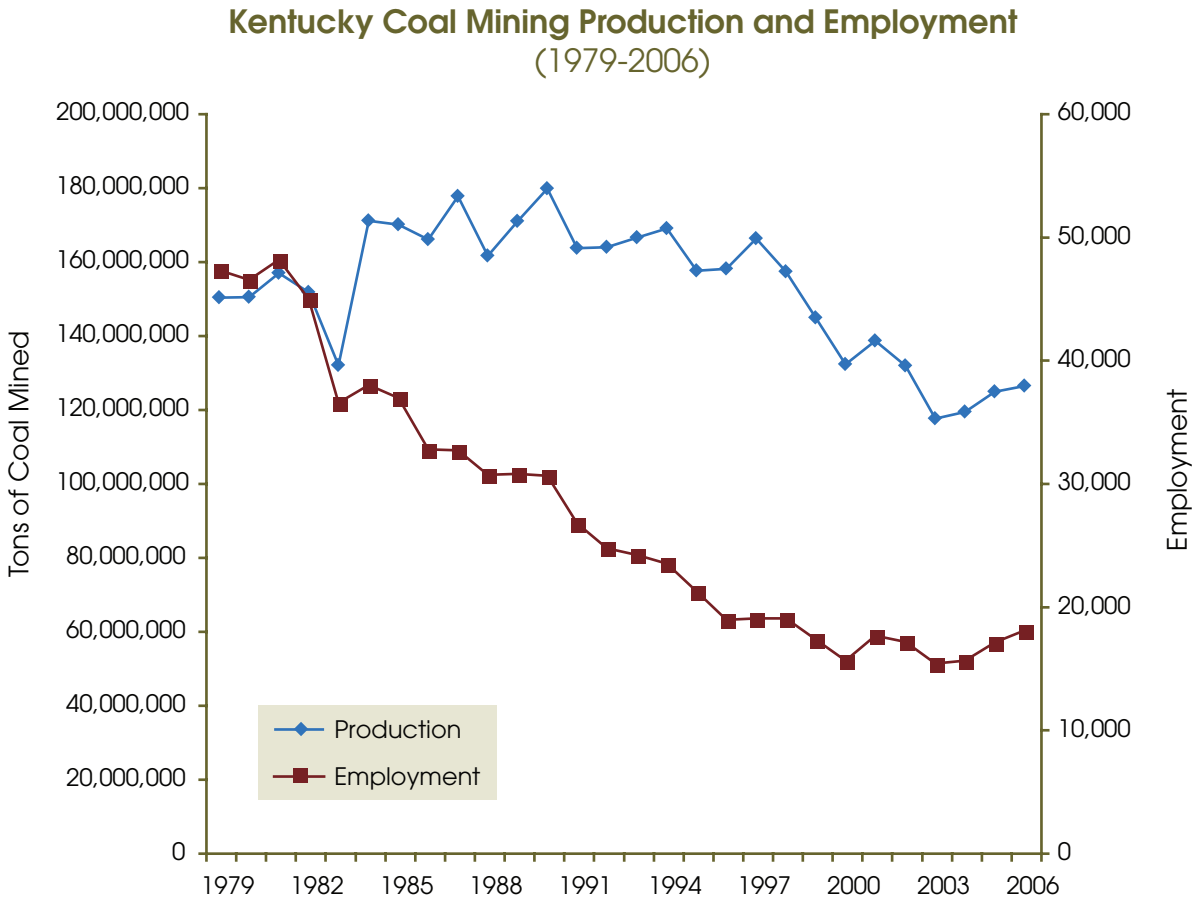

Figure 2: Kentucky Coal Mining Production and Employment.
Source: Kentucky Coal Facts (http://www.coaleducation.org/Ky_Coal_Facts/default.htm)
For more information on the economy of coal in Kentucky, visit www.maced.org/coal.

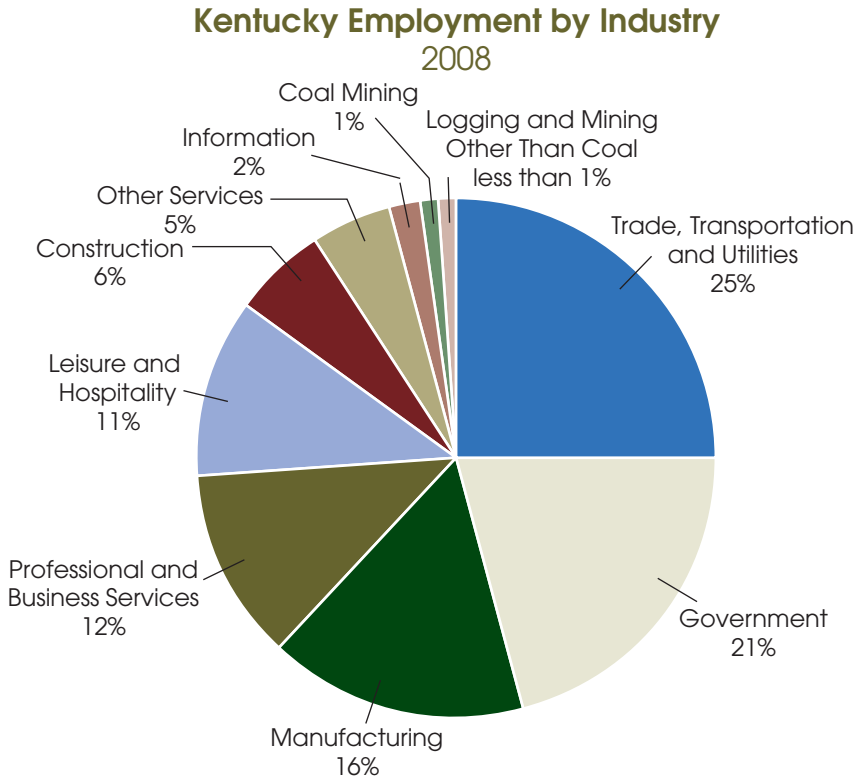

Figure 3: Kentucky Employment by Industry.
Source: Kentucky Workforce Investment, Current Employment Statistics, 2008 Annual Data.

Recommendations

The Impact of Coal on the Kentucky State Budget suggests three key recommendations for Kentucky leaders.

- **Compare future investments in coal to investments in energy alternatives.**
  The state launched a period of more active energy policy with the recent passage of House Bill 1 in a 2007 special session, House Bill 2 in the 2008 General Assembly, and the release of Governor Beshear's new energy plan. Kentucky invests modestly in renewable energy and energy efficiency, while it aggressively pursues policies to support coal and invest in new coal technologies. As the nation and the world begin to reduce dependence on fossil fuels, the Commonwealth must make strategic energy choices based on the full costs and benefits of the options before us.

- **Pursue economic diversification.**
  As this report indicates, the costs associated with hosting the coal industry are significant. The long-term downward trend in coal employment and the approaching end of low coal-fired electricity prices further diminish the industry's economic development benefits. While no one knows for sure how long coal will be mined in Kentucky, it is not a renewable resource. We must work harder to achieve lasting economic diversification throughout Kentucky and its coalfield communities.

- **Examine the way coal is taxed and subsidized in the state.**
  While the coal severance tax is often referenced for its contribution to Kentucky communities and the state budget, its benefits are diminished when the costs associated with hosting the coal industry are more fully represented. At the same time, tax expenditures for the coal industry are a set of growing but largely hidden subsidies that reduce revenue to the state budget. Taxation theory suggests higher taxes on activities, like the mining of coal, which cannot be relocated to other states. But the Commonwealth has not adjusted several coal-related taxes and fees in many years.[3] Kentucky should examine its rate of taxation and use of subsidies and think strategically about the needs of the Commonwealth and the best path to a prosperous future.

The energy landscape is changing in the U.S. and beyond. Kentucky coal faces a challenging future. Kentuckians must think carefully about how we will engage the coming transition. We must move forward making informed choices about policy and public investments with a clear and honest accounting of the costs and benefits of our choices. *The Impact of Coal on the Kentucky State Budget* raises important questions to consider as we chart our economic and energy future.

The Impact of Coal on the Kentucky State Budget

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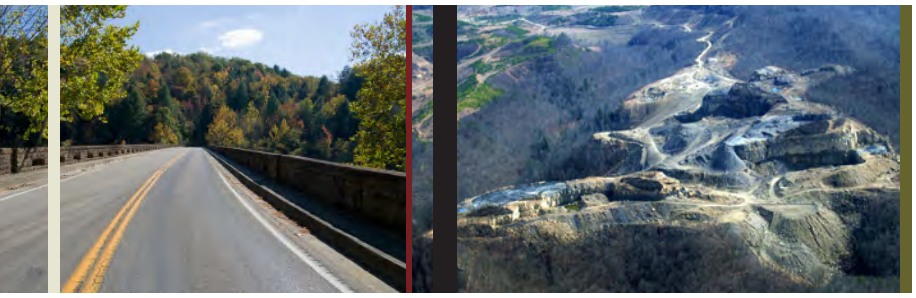

Introduction

Coal has long been important in Kentucky. Generations of Kentuckians have earned a living and supported their families by mining coal. Kentucky coal helps to keep electricity rates in the state low and is a source of tax revenue, particularly through the coal severance tax. Today the coal industry continues to provide well-paying jobs to thousands of residents in eastern and western Kentucky.

Public discussion of coal often references these economic benefits. Coal's full impact on the state, however, is more complex and problematic. The industry imposes major costs, including its impact on health, environment and quality of life in coalfield communities and beyond, and the costs of the coal infrastructure and regulatory systems. The boom-and-bust cycles of the industry, the long-term downward trend in coal employment and the persistent poverty of coal-producing counties add to the complexity.

The story this report tells is troubling. While coal generates significant revenues, its costs are considerable. Major public expenditures go into maintaining the coal haul road system; operating the health, safety and environmental protection systems necessary for coal; supporting training and research and development for the industry; and providing various tax breaks and subsidies. Without including harder-to-quantify costs of negative externalities from the industry, the estimated net cost to the state is over $100 million annually.

Given the considerable costs, Kentuckians need to carefully consider the role of coal in our economy. The rapidly changing energy market and policy environment create new challenges for the industry. Increasing concerns about climate change and a push for cleaner forms of energy across the country mean an uncertain future for coal. These pressures will inevitably raise the price of coal-fired power relative to other cleaner sources, increasing electricity costs for Kentucky residents and impacting coal's ability to compete in the energy marketplace.

How the energy future unfolds has special implications for the state's coal-producing regions. Long dependent on coal as a source of jobs and electricity, Appalachian Kentucky faces huge economic challenges that require smart planning and immediate action.

Decisions, especially concerning public policy and the investment of public dollars to meet energy and economic challenges, should be made based on a clear understanding of the full costs and benefits of the alternatives before us. *The Impact of Coal on the Kentucky State Budget* is intended to contribute to that conversation.

Methods

The Impact of Coal on the Kentucky State Budget provides an estimate of the annual impact of the coal industry on *The Budget of the Commonwealth of Kentucky*. The report compares coal-related tax revenues to coal-related public expenditures in three parts: 1) those related to the industry's activity; 2) those related to individuals directly employed by the industry; and 3) those related to employment indirectly attributable to the coal industry.

This report is an update of a 1986 MACED study titled "A Public Sector Income Statement for the Coal Industry in Kentucky, 1985-2000," authored by Dr. Richard Sims. Sims, a former Kentucky Legislative Research Commission (LRC) economist, also authored a 1980 LRC study titled *The Fiscal Impact of the Kentucky Coal Industry*. The fiscal impact report builds on the methodology of Sims' 1986 MACED study while updating it with new information and approaches where appropriate. While not perfectly comparable because of methodological changes, the two studies come to similar conclusions. The 1986 report estimated a net fiscal impact of –$130 million for 1985 and projected an impact of –$57 million in 2000. Our estimates arrive at a net fiscal impact of –$115 million for 2006.

The data included in this report are for 2006, the most recent year for which data across categories and sources are available. Our analysis includes facts and figures for state fiscal year 2006 except in cases where only calendar year 2006 numbers are available. Because we rely on multiple estimates, our figures cannot be precise; however, we make every effort to use estimation methods that others use and find to be reasonably accurate.

In an effort to isolate coal's net impact on the state budget, this report uses only general fund and road fund revenues and expenditures. The analysis excludes federal funds allocated to Kentucky and various restricted funds that agencies raise and then use for their own purposes. The report uses a combination of actual spending and revenue numbers from the Revised Fiscal Year 2006 *Budget of the Commonwealth* and data provided by various state agencies upon request. All references to government agencies and offices reflect the organizational structure and unit titles in place in 2006. We maintain the 2006 names for the sake of consistency with cited tax and budget documents.

Section I, "Direct Industry Revenues and Expenditures," presents state budget impacts of industry activities. We examine taxes paid by the coal industry and state spending to support the industry. This section includes revenues from the coal severance, sales, corporate income and unmined minerals taxes as well as coal-related transportation and permit fees. We include expenditures to maintain the coal haul road system, the coal regulatory system, job training and research and development. We also include coal-specific tax expenditures in our calculation of state expenditures. Tax expenditures refer to the estimated value of foregone revenues from tax exemptions or subsidies created for particular industries or groups. Tax expenditures are a form of spending similar to direct appropriations. The state offers a growing number of tax exemptions and subsidy programs directly targeted to the coal industry, making a study of coal's fiscal impact incomplete without them.

Section II, "Direct Employment Revenues and Expenditures," provides estimates of the fiscal impact of direct employment in the coal industry. We use the state's *Kentucky Coal Facts* as a source for data on coal industry employment and wages. Combined with reported state revenues and expenditures, these data allow us to estimate tax revenues generated by coal employment and coal employees' share of state expenditures.

Section III, "Indirect Employment Revenues and Expenditures," applies economic impact multipliers to direct employment and income figures to estimate the economic and state budget impact of employment indirectly attributable to coal. Policymakers and planners use economic impact analyses to estimate the effects of development projects on local and regional economies. These analyses rely on what economists call economic development or impact multipliers. Multipliers allow analysts to make projections about the economic impact of proposed developments or firm closures. In the case of the coal industry in Kentucky, the Kentucky Coal Association and state officials use revenue numbers based on impact models to discuss the importance of the coal industry to the state's economy.

The indirect impact figures rely on *Kentucky Coal Facts*, state budget data and the Bureau of Economic Analysis RIMS II 2006 multipliers for the Kentucky coal industry. Indirect employment includes those employed in industries that supply the coal industry and those that provide goods and services to coal employees. In this section of the report, we explain the economic impact modeling that we use, concerns about these models and our rationale for using them.

The Impact of Coal on the Kentucky State Budget provides important information for better understanding the impact of coal in Kentucky, but it does not present a complete picture. We include a discussion of issues and concerns not addressed in our analysis as a means of putting our data in the larger context of more recent policy decisions and the broader impact of the industry on the state. The report concludes with a brief discussion of our findings and the policy implications that stem from this work.

I. Direct Industry Revenues and Expenditures

Revenues	
Severance Tax[4]	$224,490,111
Unmined Minerals Tax[5]	2,118,777
Property Tax	—[6]
Extended Weight Decals and Registrations	3,582,940
Sales Tax on Coal Company Purchases	59,640,000
Strip Mining & Reclamation Fees	1,412,920
Corporate Income Tax	11,928,000
Total Revenues	**$303,172,748**
Tax Expenditures (Foregone Revenues)	
Corporation Income: Exclusion of 50% of Coal Royalties	Minimal
Corporation Income: Coal Conversion Credit	($200,000)
Corporation Income: Coal Incentive Tax Credit	(100,000)
Sales: Coal Used in Manufacture of Electricity	(78,700,000)
Energy and Energy Producing Fuels	(5,753,280)
Total Tax Expenditures	**($84,753,280)**
On-Budget Expenditures	
Commerce	($2,273,200)
Environmental and Public Protection	(22,594,195)
Education and Workforce Development	(6,731,075)
Transportation	(238,869,358)
Subtotal	**($270,467,828)**
Total Expenditures	**($355,221,108)**
Net Impact	**–$52,048,360**

Figure 4: Industry-Specific Impact on General and Road Fund Revenues and Expenditures

As corporate entities severing coal and doing business in the Commonwealth, coal companies pay a variety of taxes and fees. These taxes and fees provide revenue streams in the state budget that help to support the various goods and services provided by the state to the coal industry. This section provides estimates of state revenues from the coal industry along with estimates of on- and off-budget state spending to support the coal industry and its activities in the Commonwealth. We use *The Budget of the Commonwealth* Revised Fiscal Year (FY) 2006 and state revenue figures to document and estimate both revenues and expenditures directly associated with coal. Each item includes a description as well as the method used to calculate the revenue or expenditure estimate. We find that the state receives approximately $303 million directly in revenues from the coal industry and spends roughly $355 million directly supporting the industry for a net fiscal impact of –$52 million for FY 2006.

Direct Industry Revenues

Coal provides several direct revenue streams for the state. The largest stream is the coal severance tax, but coal also generates revenue from the unmined minerals tax, extended weight decal and registration fees, sales tax on company purchases, strip mining and reclamation fees and corporate income tax.

Severance Tax

According to *The Budget of the Commonwealth*, the coal severance tax serves two key functions: "to improve the environment for new industry and to improve the quality of life of the residents."[7] In the year 2006, the coal severance tax generated $224,490,111 in general fund revenue.

Unmined Minerals Tax

The unmined minerals tax is a property tax assessed on the value of the coal that remains underground. The state real property tax rate for 2006 was 12.8 cents per $100 of assessed value. The total amount collected in local and state taxes in 2006 was $14,369,975.[8] Of this, $2,118,777 went into the state's general fund under property tax revenue. This revenue stream is related to coal that has not yet been mined. Ongoing mining means this is ultimately a declining revenue source.

Extended Weight Registration Permits and Coal Haul Decals[9]

Trucks carrying more than 80,000 pounds are subject to a $1,410 registration fee for the 73,281-80,000 pound weight class.[10] Coal truck drivers pay an additional fee for the privilege of carrying extremely heavy loads not generally permitted on state roads.

All coal trucks purchasing extended weight decals must register their vehicles in the 73,281-80,000 pound weight class, but not all 3,220 extended weight coal trucks pay full registration in the state of Kentucky. Trucks hauling freight in more than one state have apportioned registration and pay partial fees based on how much of their total hauling occurs in each state. The Road Fund receives 70 percent of these revenues and the other 30 percent go to the counties. An estimated 65 percent of extended weight coal haul trucks are fully registered in Kentucky, generating more than $2 million in state revenue. The remaining 35 percent log approximately 50 percent of their miles in Kentucky and generate roughly half a million dollars in state revenue. The Commonwealth receives an estimated $2.6 million in total revenue from truck registrations for extended weight coal haul trucks.[11]

In the mid-1980's the state instituted the extended weight coal or coal by-products road decal permit system in order to legalize what had become a standard practice of loading coal to weights beyond the state limits. *Kentucky Revised Statutes (KRS)* 177.9771 states that "the 'extended weight coal or coal by-products haul road system' shall consist of all state-maintained toll roads or state-maintained roads which were previously toll roads and the public highways over which quantities of coal or coal by-products in excess of fifty thousand (50,000) tons were transported by motor vehicles during" the year prior to the budget year in question.[12] The state sells extended weight decals to coal truck operators and those who purchase the decals are exempt from standard state maximum weight limits. The guidelines and fee schedule for the extended weight decals appear in Figure 5.

Vehicle	Total Number of Axles	Maximum Weight (lbs.)	Toler-ance	Annual Decal Fee
Single Unit Truck	3	90,000	5%	$160
Single Unit Truck	4	100,000	5%	$260
Tractor-semi-trailer	5+	120,000	5%	$360

Figure 5: Extended Weight Decal Fees

In 2006, 3,220 extended weight decals generated $960,974 in revenue to the state of Kentucky.[13]

In a 1995 report, researchers at the Kentucky Transportation Center found that the registration and extended weight revenue is offset by the reduction in truck registrations that accompanies the increased carrying capacity of coal trucks.[14] Because the state grants the coal industry exception to standard weight limits, the state effectively loses revenue from additional truck registrations that would be purchased if the industry had to use more trucks to haul the same amount of coal. We can also note that this exception reduces the number of jobs provided by the industry as fewer truck drivers are needed to haul coal and the increase in weight limits adds to wear and tear as well as fatal and injurious accidents on the road.

The extended weight registration and decal fees are not the only sources of revenue related to transportation. Due to data limitations, coal's share of transportation tax revenue from basic vehicle and fuel taxes is rolled into transportation taxes listed later in this report.[15]

Sales Tax on Coal Company Purchases

The state generates revenue when coal companies make purchases in the state and pay sales taxes on those purchases. Coal companies, just like other corporations, are able to take advantage of a wide range of tax exemptions—some of which apply to purchases. We do not account for exemptions beyond those specific to coal in this report. Our estimate of sales tax receipts for coal company purchases is based on methods used by University of Kentucky researchers in a 1996 study of the economic impact of the coal industry in Kentucky.[16] Based on interviews with coal industry executives, that report estimates coal company purchases subject to sales and use tax at 20 percent of total output. We assume the six percent sales tax rate on 20 percent of total output and estimate that the state receives nearly $60 million in sales tax revenue from the coal industry.[17]

Strip Mining & Reclamation Fees

Kentucky charges fees for strip mining and reclamation permits. These fees cover the costs of issuing permits and generate some revenue for the state's general fund. Strip mining and reclamation fees account for state general fund revenues totaling $1,412,920 in fiscal year 2006.[18]

Corporate Income Tax

Corporate income taxes are taxes assessed on the taxable net income of corporations. Kentucky does not publicly report corporate income tax revenues by industry so we cannot report actual corporate income tax revenues from the coal industry. For corporations operating in more than one state, corporate income tax payments are apportioned among the states in which they do business.

Reuter's Industry Benchmarks reports an effective federal tax rate (Trailing Twelve Months) for the coal industry of zero percent and a five year effective federal tax rate of zero percent.[19] We found no information in publications produced by the coal industry to indicate how much state corporate income tax coal companies pay.

The corporate income tax rate in the Commonwealth for 2006 was four percent for businesses with taxable net income up to $50,000, five percent for businesses with taxable net income between $50,000 and $100,000, and seven percent of taxable net income over $100,000. Beginning in 2007, the top rate was lowered to six percent.

The Kentucky coal industry reported output of $4.97 billion in 2006.[20] Annual reports of several coal and energy companies indicate wide variation in net income ranging from significant losses to 16 percent profit. Kentucky allows companies to count prior years' losses against current net income, thereby decreasing and, in some cases, eliminating any tax burden even in profitable years. This arrangement is particularly helpful to the boom and bust coal industry. In 1996 researchers at the University of Kentucky Center for Business and Economic Research (CBER) estimated Kentucky coal companies' net income at four percent of total output. Given the variation in information about net income and the lack of actual data, we use the CBER figure as our guide. We estimate net income at four percent of total output[21] and an average tax rate of six percent which accounts for portions of net income that are charged both higher and lower rates under *KRS* 141.040.[22] Using these figures, we estimate revenue to the Commonwealth of $11,928,000, about 1.2 percent of Kentucky corporate income tax revenue.

Direct Industry Expenditures

Direct industry expenditures include off-budget spending through tax exemptions and subsidies (tax expenditures) and on-budget costs including those associated with state energy policy, mine safety and regulation offices, environmental protection, workforce development and education and transportation infrastructure.

Tax Expenditures Specific to Coal

Sales and Use	
Coal Used in the Manufacture of Electricity	($78,700,000)
Energy and Energy Producing Fuels	($5,753,280)
Corporate Income	
Exclusion of 50% of Coal Royalties	Minimal
Coal Conversion Credit	($200,000)
Coal Incentive Tax Credit	($100,000)
Estimated Tax Expenditures FY 2006	**–$84,753,280**

The Budget of the Commonwealth includes a requirement that the Office of the State Budget Director (OSBD) produce a detailed report of the estimated impact of state tax expenditures. This report defines tax expenditures as

"an exemption, exclusion, or deduction from the base of a tax, a credit against the tax, a deferral of a tax, or a preferential tax rate."[23] Two of the eight principles used to guide the inclusion of tax expenditures are important to note in our discussion of those expenditures that support the coal industry (items are numbered as they are in the tax expenditure report):

(2) A tax expenditure does not include an exemption for entities, items, or transactions that are commonly and traditionally exempted from payment of taxes.
(3) A tax expenditure does not include a credit or exclusion which prevents the taxation of the same base more than once. As an example, a "sale for resale" exemption in the sales tax is not considered a tax expenditure since in the absence of such an exemption an article could be subjected to the tax multiple times as it moves through the production cycle.

The coal industry in the state of Kentucky and throughout the U.S. is subject to a variety of exemptions designed to support energy production. These expenditures effectively take away a portion of the state's potential tax revenues. Because we do not collect these taxes from the industry, other general fund monies are used to support the industry and those whose employment is attributable to the industry.

The industry benefits from exemptions particular to coal as well as broader exemptions available to other industries. In the *Tax Expenditure Analysis* summary tables, expenditures specific to coal appear under the heading "Energy Development and Coal Industry Support." Our estimates of corporate income and sales tax revenues (presented above) are high as we do not account for the various exemptions that are specific to coal. These figures help to correct those estimates and document off-budget spending. The OSBD estimated a total of $79 million in FY 2006 in sales and corporate income tax expenditures specific to coal. Coal's share of the Energy and Energy Producing Fuels (sales and use) expenditure adds an additional $5.8 million to tax expenditures to support the coal industry, bringing the total estimate to nearly $85 million.

Coal Used in the Manufacture of Electricity

The *Kentucky Tax Expenditure Report* states that, "Coal Used in the Manufacture of Electricity is exempt."[24] The total expenditure for FY 2006 is $78.7 million.[25]

Energy and Energy Producing Fuels

The "Energy and Energy Producing Fuels" tax expenditure applies to "energy and energy producing fuels used in manufacturing, processing, mining, or refining, to the extent that the cost of the energy or energy producing fuels used exceeds 3 percent of the cost of production, are exempt." The total expenditure for Energy and Energy Producing Fuels in FY 2006 is $20.8 million. Electricity accounts for 30 percent of industrial energy use in Kentucky while natural gas comprises 21 percent and petroleum 36 percent.[26] *Kentucky Coal Facts* reported that 92.2 percent of Kentucky's electricity came from coal in 2006. We calculate coal's share of the energy and energy producing fuels tax expenditure by attributing 30 percent of the total expenditure to electricity. We then attribute 92.2 percent of electricity's share of the tax expenditure to coal for a total estimated expenditure of $5.8 million.

Coal Royalties

The OSBD reports that "a corporation owning an economic interest in coal land may exclude 50 percent of any royalties received from such land if it does not deduct certain expenses related to the production of the royalty income, including percentage depletion."[27] The expenditures here are reported as "minimal" in the *Tax Expenditure Analysis* and the OSBD provides no dollar amount.

Coal Conversion Credit

According to the *Tax Expenditure Report* "corporations may claim an income tax credit equal to 4.5 percent of the purchase price, minus transportation costs, of coal consumed or substituted in heating facilities that are currently using a different source of energy."[28] The credit resulted in an estimated tax expenditure of $200,000 for FY 2006.

Coal Incentive Credit

The *Tax Expenditure Report* states that "a credit is allowed to any electric power company or any entity that operates a coal-fired electric generation plant, is an alternative fuel facility or gasification facility. The credit is equal to $2 multiplied by the increase in tons burned in the tax year over the tons burned in the base year."[29] The OSBD estimated this expenditure at $100,000 for FY 2006.[30]

Coal Severance Tax Expenditures

Coal Severance Tax Potential Revenue	$242,590,111
Coal Severance Tax Expenditures	
Transportation Expense	($17,700,000)
Thin Seam Tax Credit	($400,000)
Coal Severance Actual Revenue FY 2006	**$224,490,111**

Figure 6: Coal Severance Tax Expenditure—Impact on Revenue

In addition to sales and use and corporate income tax expenditures, the state lists two tax expenditures that support the coal industry and decrease state revenues from the coal severance tax. The "Transportation Expense" exemption and the "Thin Seam Credit" exemption reduce revenues for FY 2006 by a total of $18.1 million. Because we include an exact figure for actual coal severance tax revenue above, we do not add these expenditures to the expense side as they are already accounted for in the lower revenue number.

Transportation Expense

As described in the *Tax Expenditure Report*, "transportation expenses incurred in transporting coal from the mine mouth or pit to a processing plant, tipple, loading dock, or customer is deductible in computing gross value."[31] The transportation expense expenditure is $17.7 million for FY 2006.

Thin Seam Tax Credit

The *Tax Expenditure Report* summarizes the thin seam tax credit as follows: "A non-refundable tax credit is allowed for mining coal from thin seams or from areas with a high mining ratio. The credit is on a sliding scale from 2.25 percent to 3.75 percent of the value of the severed coal, based on the thickness of the seam, the ratio of overburden removed to coal severed, or the sulfur content of the coal." The Thin Seam Credit expenditure is $400,000 for FY 2006.

Total Tax Expenditures

Tax expenditures are an important tool for governments to promote activities that they want to encourage. Among tax expenditures to support energy development in the state of Kentucky, 98 percent of estimated tax expenditures for specific energy fuel sources support the coal industry exclusively.[32] Coal has been a cheap energy source in part because the state provides significant tax exemptions and subsidies to lower the costs of mining, processing and distributing coal.

Direct On-Budget Industry Expenditures

This section addresses expenditures specifically targeted at supporting the coal industry. We exclude all restricted and federal funds to focus solely on the industry's impact on the state general and road funds in accordance with the revenue side.

Commerce	
Office of Energy Policy	($1,873,200)
Grant for Energy Education in Schools—Coal Council	(400,000)
Environmental and Public Protection	
Mine Reclamation and Enforcement	(9,661,600)
Mine Safety and Licensing	(9,460,200)
Mine Safety Review Commission	(198,500)
Environmental Protection—Air Quality	(293,180)
Environmental Protection—Water Quality	(2,046,460)
Environmental Protection Administrative and Program Support	(934,255)
Education and Workforce Development	
Coal Academy—Mining Workforce Development	(3,000,000)
Postsecondary Education	
University of Kentucky—CAER	(2,615,032)
University of Kentucky—Mining Engineering	(1,016,043)
Consortium for Fossil Fuel Liquefaction Science	(100,000)
Transportation	
Coal Haul Road System	(238,869,358)
Total Expenditures	**–$270,467,828**

Figure 7: State Expenditures to Support the Coal Industry

Commerce: Office of Energy Policy

The purpose of the Office of Energy Policy is to promote the development of the state's energy resources and work to maintain low energy prices for the Commonwealth. Ninety-two percent of Kentucky's electricity comes from coal and the language of the policy describing the role of the Office of Energy Policy[33] indicates a significant focus on coal while also including programs for renewable energy

and energy efficiency. University, research and development, and demonstration programs include attention to Applied Energy, Clean Coal and FutureGen.[34] We classify 80 percent of the office's general fund expenditures as coal expenditures for a total of $1.9 million in FY 2006.

The state grants $400,000 per year to the Coal Council for energy education in the schools. According to *The Budget of the Commonwealth 2006-2008,* "the duties of the Council include, but are not limited to, promotion of Kentucky coal through development of market information, coordination of ongoing research and marketing programs relating to coal production, transportation, and consumption, identification of national and international market developments relating to coal, and advising coal operators and other industries seeking to enter or expand domestic or export markets."[35] The Coal Council uses the General Fund appropriation to provide materials to educate students in the public school system on the benefits of coal.

Environmental and Public Protection

The Cabinet for Environmental and Public Protection (EPP) is home to all of the Mine Reclamation and Enforcement divisions and the Environmental Protection department. The state receives significant federal funding to support much of the work of this cabinet, but we deduct those funds and restricted dollars from each division's budget in order to focus on the state's general fund expenditures on coal.

The total budget for Mine Reclamation and Enforcement is $31,037,600, with $9,661,600 coming from the state's general fund. Mine Safety and Licensing spends $9,460,200 from the general fund and the Mine Safety Review Commission an additional $198,500. Both industry and environmental groups express concern that state mine safety offices are understaffed. Too few inspectors may mean mine safety is compromised and mining impacts on air, water, land and coal field communities go unchecked.

The state's Environmental Protection Department within the EPP Cabinet had a total budget (excluding federal funds) of nearly $74 million in FY 2006. Divisions within the EPP cabinet manage environmental impact and air and water contamination resulting from coal extraction processes; waste impoundments and particulate matter produced in every stage of extraction, processing, energy production and use. With 92 percent of Kentucky's electricity coming from coal-fired power generation, a significant portion of air and water pollution in the Commonwealth is attributable to coal with development and agriculture as other major contributors.

Lacking exact figures on specific program expenditures, we look to MACED's 1986 *Public Sector Impact Statement* for direction. MACED estimated coal's share of air and water quality expenditures within EPP at 20 percent. Twenty percent of the General Fund expenditures for Air and Water Quality units are $293,000 and $2 million respectively. Administrative and program support expenditures for the Air and Water Quality units, proportionate to work related to coal, total more than $934,000.

Education and Workforce Development

The state grants $3 million to the Coal Academy, a workforce development program offered through the Kentucky Community and Technical College System.

In addition, the University of Kentucky is home to the Center for Applied Energy Research (CAER) which is funded in part by the general fund. CAER conducts research on a wide range of energy sources and technologies, a significant portion of which concerns coal. In FY 2006, state funding for CAER totaled $4.7 million. In order to estimate what portion of the CAER budget supports work on coal, we counted the number of research staff whose areas of expertise include coal-related work. We found that 29 of the 52 research staff listed on the CAER web site include coal related research and technology development in their areas of research. Based on this count, we estimate that coal's share of funds received from the state totals around $2.6 million.

The University of Kentucky is also home to a mining engineering program that received support from the state in the amount of $1,016,043, and the Consortium for Fossil Fuel Liquefaction Science received approximately $100,000 from the General Fund.[36]

Coal Haul Road System and Damages

The coal haul road system has long been a subject of study and concern. Kentucky's coal haul road system consists of rural roads, state highways and interstates that facilitate the transport of coal from mine mouth to tipple, train, barge and power plant. These roads withstand tremendous wear and tear and require frequent extensive maintenance. The coal haul road system includes county and local roads as well as state maintained roadways. The estimates that follow reflect Kentucky Road Fund expenditures for the coal haul road system (Please see Technical Appendix for a review of relevant research and a full explanation of various coal haul road calculations).

Pavement construction, reconstruction and repair are expensive and even more so when roads must meet specifications for carrying heavy trucks. The Kentucky Transportation Center (1995) reports overlay costs of $100,000 ($132,280 in 2006 dollars) per mile for a four-lane roadway and an average $500,000 ($661,420 in 2006 dollars) per mile for thicker overlays. Even roads that do not require pavement overlays will still require annual maintenance including crack and joint filling, patching, chip sealing and pothole repair. Costs for this type of annual maintenance are higher in coal producing areas than in the rest of the state (an average $397 higher per mile).[37] The extended weight (EW) system adds costs above and beyond the already higher costs resulting from coal truck damage throughout coal producing and impacted counties. With these costs in mind, we construct three models of total cost and then use the average of the three estimates for our fiscal impact analysis.

All three models use the previous estimate of the Kentucky Energy Cabinet that 75 percent of the costs of maintaining the nearly 4,000 miles of coal haul roads are attributable to the coal industry.[38] Model 1 is based on road service needs and estimated per mile costs; Model 2 uses Vehicle Miles Traveled for the coal haul road system and the 75 percent cost allocation to estimate the share of expenditures attributable to coal; Model 3 combines that estimate with the debt service and state expenditures to support county coal haul road maintenance to arrive at an estimate that reflects more of the long-term costs of the coal haul roads.

The service life of coal haul roads is between two and four years, rather than the standard 20 years. An ideal overlay rotation would have the state placing new overlay on one-fourth of the coal haul road system each year to accommodate the shorter service life and maintain road quality and safety. To support loads over 80,000 pounds, the coal haul road system requires thicker overlays than other roads. We apply the average cost of $661,420 per mile of four-lane road to the coal haul road system and assume that two lane roads cost about half as much (though they are likely to cost more than half given that the shoulder costs are the same or higher for the narrower roads). We find that 17.8 percent of state-maintained coal haul roads were four-lane rural roads in 2006 and 82.2 percent of coal haul road miles were two-lane roads.[39] The total cost to overlay one-fourth of the system is nearly $365 million. If 75 percent of the cost is attributable to coal, then we estimate coal's share at $273.5 million for FY 2006. This scenario is based strictly on cost and an estimate of likely need for the road work based on coal truck activity and damage data. We know that the state is likely to use less expensive maintenance to help defer costs to a later date. Subsequent models are based on actual road spending for FY 2006 and are more likely to reflect that the state defers some costs each year to accommodate budget constraints. Keep in mind, however, that any year's expenditures will include some expenses that were deferred in prior years.

The remaining models use vehicle miles traveled (VMT) as a multiplier for cost allocation. VMT cover some of the added costs associated with higher traffic on these roads than would be there without the coal industry, but do not incorporate the difference between one mile of coal truck travel and one mile of passenger car travel. Heavy trucks cause significant damage to roads whether they are coal trucks or not. The extended weight exception to weight limits means that coal trucks carry heavier loads than other trucks and the resulting wear and tear tends to be geographically concentrated. The types of trucks and axle configurations of many coal trucks cause more damage than the large five or six axle trailer trucks that traverse the interstates with heavy loads of consumer goods. These trucks no doubt cause significant damage, but more axles mean a better distribution of weight to reduce impact on the roads. The axle loads of straight trucks, often traversing mountainous rural roads in the coalfields, have a disproportionate impact on state costs.

The Kentucky Transportation Center (KTC) found that the extended weight (EW) coal haul road system carried 19% of VMT on state maintained roads. If we use VMT as a crude estimator and apply coal county base system VMT estimates to the non-EW coal haul roads, we find that the total coal haul system carries roughly 23.9 percent of travel on state maintained roads. Using VMT to determine a share of costs assumes that administrative, capital and maintenance costs vary by VMT. Without regard to vehicle weights, according to this model, the coal haul road system is responsible for $273.6 million of spending in the FY 2006 state budget. Following on earlier studies, we estimate that 75 percent of road costs on roads that carry coal are attributable to coal hauling (given that coal hauling can reduce service life from 20 years to two to four years, this seems like a reasonable estimate). Using this method, we estimate coal's share of maintenance costs on the coal haul road system to be $205.2 million.

This estimate represents a reasonable estimate of many road related costs. However, the method underestimates capital expenditures for grade, drain, surfacing and resurfacing work and maintenance and operations spending

on structures. Without definitive information on axle configurations for the 3,000-4,000 coal trucks operating in the state and the mileage and payload of those trucks, it is difficult to arrive at accurate cost allocation estimates. These complexities are exacerbated by the fact that we know that many trucks underreport activity or operate off the radar altogether.

In addition, expenditures specific to the Resource Recovery Road System include a state allocation of $1,003,000 to the counties to help cover costs associated with county maintained roads that are part of the coal haul road system and $38,838,600 in debt service for prior construction on the Resource Recovery System. If we take these funds out of the road fund before calculating coal's share of remaining road fund expenses and then add them back in on top of the coal industry's share of all other expenses, we can attribute $237.9 million to the coal industry.

State record-keeping and the inherent limits to regulatory control and monitoring mean that we cannot provide precise figures on the coal industry's share of road expenses to support their use of the roads for hauling coal and equipment. Our purpose is to provide some information that sheds light on the range of costs associated with the industry's presence so that we might better assess the state's role in supporting the activities of the industry.

Given the myriad issues surrounding the task of cost allocation, we use an estimate that accounts for the strengths and weaknesses of the three models. If we take the average of the three models above (Model 1 based on regular thick overlay rotation, Model 2 based on VMT and Model 3 including VMT and debt service and state road fund support for county maintenance of coal roads), we arrive at an estimated coal haul road cost of $238.9 million for FY 2006.

These costs are high, but not unexpected. As we weigh various options, the roads are a significant cost that will vary based on the energy resources in which we choose to invest.

Direct Industry Revenues and Expenditures: Net Impact

A review of coal industry-generated revenues to the state and expenditures from the state suggests that the industry actually costs more than it brings to the state. In our estimation, the industry costs the state roughly $52 million without significant attention to health and social externalities and with limited accounting for environmental impact.

In the next two sections, we look at the impact of the industry on employment and earnings in the state and the resulting impact on revenues and expenditures. Coal employs thousands of Kentuckians in the eastern and western coal fields. Coal employees pay taxes on their earnings and consumption, thus generating additional revenues and expenditures for the state.

II. Direct Employment Revenues and Expenditures

Over the last century, the coal industry attracted thousands of workers to well-paying mining jobs in the Kentucky coal fields. Those employed by coal contribute to *The Budget of the Commonwealth* through the taxes they pay and are also recipients of state services funded by their tax dollars. We use employment and earnings data to estimate state revenues and expenditures attributable to direct employment in the coal industry.

Direct employment generates state revenues through personal income, sales and use, property and motor vehicle taxes. The state uses the revenues to pay for infrastructure, schools and services for those employed by the industry. Direct employment in the coal industry by itself is a net gain for the state of nearly $10 million.

Direct Employment	
Revenues	
Personal Income Tax	$45,086,947
Sales and Use Tax	23,067,740
General State Property Tax	4,414,260
Motor Vehicle Taxes (excluding extended weight decals and registration fees)	10,471,444
Subtotal	**$83,040,392**
Expenditures	
Share of State Expenditures	($73,140,605)
Net Impact of Coal Employment on State Budget	**$9,899,787**

Figure 8: State Revenues and Expenditures Associated with Direct Employment in the Coal Industry

Employment And Earnings

Kentucky Coal Facts reported coal employment at 17,669 people for 2006.[40] Their figures excluded several counties with "less than three employers or one employer with 80 percent of the total county miner workforce."[41] These data are withheld to protect company privacy. We used output figures by county paired with available employment data to arrive at an estimate of total coal employment. Statewide coal employed 17,903 people, less than one percent of employment in 2006.[42]

Year	Direct Employment in Coal Mining in Kentucky[43]	Total Kentucky Employment	Percent of Employed Kentuckians Directly Employed in Coal Mining
2006	17,903	2,029,449[44]	.88%

Figure 9: Mining Employment in Kentucky

In coal producing counties, coal employs a significantly larger portion of the population.[45] Miners do not necessarily live in the counties in which they work, but if aggregate coal county population[46] is used as the primary population from which mining employees are drawn, we find that coal mining accounts for just under five percent of coal county employment in 2006.[47] The industry plays a greater role as employer in the coal counties than statewide, but the share of employment in coal is relatively small even in those counties.

Wages are good for those employed directly in the mining industry: the statewide average weekly wage was $1,126.30 in 2006.[51] Mining wages vary significantly by company and position, but those earning at or above $50,000 per year earn well above the average wage in the eastern Kentucky mining region where poverty rates hover around 30 percent. The employment and earnings figures allow us to estimate total state revenues and expenditures associated with coal employment.

Direct Employment Revenues

Revenue from taxes paid by those employed in the coal industry total an estimated $83 million in FY 2006. Coal industry employees pay personal income, sales and use, state property, motor vehicle and fuel taxes. Precise figures for coal employee tax contributions are not available (nor would they be for any group of citizens) so for each tax, we calculate an estimate based on available data.

Personal Income Tax

We estimate that 17,903 Kentuckians were directly employed in mining earning $1,048,533,659 in Fiscal Year 2006.[52]

The Kentucky Office of the State Budget Director estimates the average effective individual income tax rate at 4.3% of Kentucky Adjusted Gross Income. This average encompasses variations in pay scale, tax brackets and allowable deductions. Using the data available, we estimate Kentucky's state revenue from personal income taxes paid by those directly employed by the mining industry to be over $45 million.

	Direct Impact ($2006)[48]	Additional Direct Impact ($2006)[49]	Total Direct Impact ($2006)
Output	$4.97 billion	-- [50]	$4.97 billion
Worker Earnings	$1,034,834,951	13,698,708	$1,048,533,659
Employment	17,669	234	17,903

Figure 10: Output, Earnings and Employment Impact

	Coal Wages	Effective Tax Rate	Individual Income Tax Revenue from Coal Employees	Share of Total State Revenue from Individual Income Tax
2006	$1,048,533,659	4.3%	$45,086,947	1.5%

Figure 11: Wages and Income Tax

Sales Tax Receipts

When individuals employed by the coal industry spend their money in the community, they generate state sales tax revenue. Kentucky has a six percent state sales tax rate. Generally, the portion of an individual's income paid in sales tax declines as income rises. However, sales tax exemptions on goods considered to be necessities temper this regressive character. Individuals do not pay sales tax on food, prescription medications or residential utilities.

Based on wage and employment figures for the state of Kentucky, we can safely assume that most of those employed directly by the mining industry fall into the middle class category.[53] Because people do not spend all of their money on consumption, the effective sales tax rate for the middle class is approximately three percent of their total income.[54] Using earnings from coal employment and average sales tax expenditures for the middle class, we estimate that more than $23 million in state sales tax revenue is attributable to direct employment in the coal industry.

General State Property Tax

State property taxes generate revenue from taxes on real, tangible and intangible property, motor vehicles, bank deposits, distilled spirits, marginal accounts, omitted property tax, delinquent taxes from prior years, apportioned vehicles, public service companies, domestic life insurance, retirement plans and building and loan association capital stock. We use coal's share of state employment to determine the share of state property tax revenue attributable to the coal industry and coal industry employment, which accounted for .88% percent of total state employment in 2006.[55] The estimate assumes that property ownership is distributed proportionately by employment without attention to earnings. Jobs directly attributable to coal range from temporary work providing inconsistent wages to high-end technology and professional services and reflect wide income variation found throughout the economy. Calculating coal-related revenues from general state property taxes as a proportional share based on employment provides a reasonable estimate for our purposes. Using this calculation, we estimate that $4.4 million in general state property tax revenues is attributable to the coal industry and coal employment.

Coal-Related Motor Vehicle Taxes (excluding extended weight decals and extended weight registration fees)

The coal industry creates revenue for the Commonwealth through taxes associated with its extensive use of transportation to move coal from mine to tipple and beyond. Additionally, those directly employed by coal generate motor vehicle taxes from their use of vehicles on public roads. In MACED's 1986 *Public Sector Impact Statement*, Sims assumed that coal's share of general vehicle and transportation taxes was approximately proportional to coal's share of employment. We follow the earlier MACED methodology and assume coal's share of total vehicle and transportation revenue, both from industry activity and from the vehicle and fuel taxes paid by those employed in the industry is proportional to coal's direct employment in the state. Note that coal industry revenue, beyond the extended weight registration and decal revenue noted earlier, is covered in this figure. In other words, this figure includes vehicle and fuel taxes attributable to the industry (and not covered by registration and decal fees) and its direct employment. Data limitations did not allow for a more precise method. Based on these assumptions, motor vehicle tax revenue directly attributable to coal is estimated at $10.5 million.

Total Revenues

Direct employment in coal generates more than $83 million in tax revenues. The coal industry provides many good jobs that contribute to the state's tax base and that stimulate activity throughout the economy. A large portion of the revenue generated through coal employment supports educational and infrastructure needs of those employed in coal as well as their share of all other public goods and services.

Direct Employment Expenditures

Just as the coal industry generates state revenue by employing residents, those residents require support and services provided by the state. Coal employees, like all residents, use schools, roads and other services. A proper estimate of coal's fiscal impact must include not just the revenues generated from employment but also the costs associated with supporting that employment.

Expenditures to support coal employees are calculated based on direct coal employment as a proportion of total state employment. We subtracted coal industry expenditures (excluding tax expenditures as these funds are not reflected in general and road fund expenditures, but rather, in foregone revenue) from the total general fund and road fund expenditures and then multiplied the remainder by coal's share of state employment to arrive at overall state expenditures attributable to coal employment. These figures include money spent to support the industry that are general infrastructure and standard state functions enjoyed by all industries and businesses in the state as well as money spent to support the portion of the labor force employed as a result of the industry's presence in the state.

People directly employed by the industry might live in Kentucky without the presence of the industry, but economic impact studies assume they would not. Economists, planners and policy-makers present the impact of a given development project or industry as if the alternative to the project or industry was no jobs or income. The models facilitate cost-benefit analyses but should be used with the built-in artificial assumptions in mind. We estimate coal employees' share of state expenditures to be $73 million.

Net Impact Of Direct Employment In Coal

The coal industry provides thousands of good jobs for Kentuckians. The level of employment in coal is far lower than it once was, but mining jobs pay strong middle class wages that contribute to state revenues. The net impact of direct employment in coal is nearly $10 million: direct employment revenues exceed direct employment expenditures by $10 million.

Total Direct Impact

Coal industry activities generate significant revenue for the state, but they also exact some high costs. Direct employment revenues surpass direct employment expenditures, but not by enough to cover the direct costs of hosting the industry. We estimate net impact of the industry and its direct employment to be –$42 million (Figure 12).

Revenues	
Industry	$303,172,748
Direct Employment	83,040,392
Total Revenues	**$386,213,140**
Expenditures	
Industry (Including Tax Expenditures)	($355,221,108)
Direct Employment	(73,140,605)
Total Expenditures	**($428,361,713)**
Net Impact of Coal Industry and Direct Employment	**–$42,148,574**

Figure 12: Net Impact of Coal Industry and Direct Employment

Direct industry and employment impacts combined do not reflect the total contributions that the industry's presence makes to the state economy or to public funds in the Commonwealth. The industry triggers economic activity and employment in supply and other related industries, and direct employment in coal leads to employment in sectors that serve those employed by the industry. In coal and other industries, the indirect economic impact is often cited, but the focus remains on the associated benefits and not the costs. In the next section, we explore the indirect economic impact, or spill-over effects, of the coal industry in Kentucky.

III. Indirect Employment Revenues and Expenditures

Indirect revenues and expenditures include tax revenues generated by employment in industries that supply the coal industry and employment in sectors that serve those directly employed by coal. We use economic development multipliers for the coal industry in Kentucky to estimate the indirect economic impact on jobs, earnings and, by extension, state revenue.[56] To simplify, we will include employment in supply industries as well as employment induced by worker spending together under the category of "indirect" impact.

Economic impact multipliers use direct employment projections and information on inflows and outflows related to and stemming from the industry, as well as consumer behavior in a particular geographic location, to determine the spill-over effects of a specific development project (i.e. a manufacturing plant, athletic stadium or large retail store) or firm closing (i.e. closing a manufacturing plant).

Multipliers, in their most complete form, are determined by examining primary data on economic inflows and outflows in the specific region of the proposed site. The multiplier accounts for both increases in economic activity among businesses that will supply the new project and increases among businesses that will serve those employed by the new development. Economic impact analyses rely on several assumptions to provide guiding estimates.

In order to estimate the fiscal impact of the coal industry on the state budget in Kentucky, we model the economic impact in a way that is comparable to prevailing models employed by stakeholders in the state. *Kentucky Coal Facts* uses updated versions of the models produced by the Center for Business and Economic Research in 1996 which employ the Regional Input-Output Modeling System (RIMS) multipliers available through the Bureau of Economic Analysis (our multipliers reflect RIMS updates since the

Kentucky Coal Facts 2007-2008 was published).[57] The RIMS II economic impact multipliers allow us to determine those impacts on state revenue and spending that are dependent on total employment and earnings related to the industry's presence in the state.

The RIMS II is based on an input-output accounting table that shows inputs purchased and outputs sold. First, industry data from across the country are used to create the industry-by-industry requirements table. Next, the adjusted national table is used to prepare a regional industry-by-industry direct requirements table, and finally, a regional industry-by-industry total requirements table is used to derive regionally specific economic impact multipliers. Each step in adjusting the national tables to regionally specific industry tables involves additional assumptions regarding inputs and outputs. More localized impacts require further data adjustments.

The RIMS II, and all economic impact multipliers, is surrounded by criticism of the models based on the assumptions built into the models and the resulting limits of their applicability and accuracy. The model assumes that all direct, indirect and induced effects would not otherwise occur without the project. The absence of the counterfactual—meaning we really have no way of knowing or modeling what activities would occur without the project—is problematic. The base assumption of the RIMS II, and all economic multiplier models, that places all other economic activity on hold is significant and presents obvious problems under the best circumstances. In addition to these concerns, the application of this method to an industry that has been in the region for more than 100 years and is tied to a place-specific natural resource violates basic principles of a model designed to assess the impact of economic shocks such as development projects or firm closures.

With these limitations and caveats clearly in mind, it is important to have more substantive analysis in order to weigh the benefits of one set of choices against another. Because the state of Kentucky and the coal industry in Kentucky use these impact multipliers to support the economic benefits of coal to the state, we think it makes sense to engage the discussion based on some common ground shared analysis, but with the full revenues and expenditures included in the model. The industry and employment figures in the first section of this paper tell part of the story; impact multipliers allow us to complete the analysis by adding the indirect or spill-over effects.

Indirect Employment Revenues	
Coal-Related Personal Income Tax	$65,177,691
Coal-Related Sales and Use Tax	33,346,726
Coal-Related General State Property Tax	12,927,160
Coal-Related Motor Vehicle Taxes (excluding extended weight decals)	30,057,785
Subtotal	**$141,509,362**
Indirect Employment Expenditures	
State Expenditures to Support Citizens Employed as an Indirect Result of the Coal Industry's Presence	($214,590,042)
Net Impact	**–$72,682,738**

Figure 13: State Revenues and Expenditures Indirectly Attributable to Coal

We find indirect employment attributable to the coal industry generates an estimated $142 million in state revenue. State expenditures to support those employed as an indirect result of the coal industry's presence total an estimated $215 million for a net fiscal impact of negative $73 million (Figure 13). The imbalance between revenues and expenditures reflects the prevalence of low-paying jobs in support industries.

Indirect Employment Revenues

The presence of the coal industry creates downstream employment (employment in related sectors—trucking, equipment supply and other related industries), re-spending or induced employment resulting from miners and mining staff spending their paychecks in their communities, and government employment as income tax dollars go to support government agencies that employ other citizens in the state.

As previously noted, earnings are above average for those employed directly in the mining industry. Wages for indirect employment vary widely, but tend to be lower than in the coal industry as evidenced by the fact that the earnings multiplier is lower than the employment multiplier. We estimate that 17,903 Kentuckians were directly employed in mining earning $1,048,533,659 in Fiscal Year 2006.[61] Indirect employment totaled 52,429. We multiply total direct earnings by the RIMS II earnings multiplier for Kentucky coal to arrive at indirect wages totaling $1.5 billion (Figure 14).

	Direct Impact ($2006)	Additional Direct Impact ($2006)	Total Direct Impact ($2006)	RIMS II Impact Multiplier for Appalachian Coal Industry in Kentucky	Indirect and Induced Impact ($2006)	Total Impact ($2006)
Output	$4.97 billion	-- [60]	$4.97 billion	2.16	$5,765.2 million	$10,735,200,000
Worker Earnings	$1,034,834,951	13,698,708	$1,048,533,659	2.4456	$1,515,760,257	$2,564,293,916
Employment	17,669	234	17,903	3.9285	52,429	70,332

Figure 14: Output, Earnings and Employment Impact

Direct Industry Revenues	**$303,172,748**
Direct Employment Revenues	**83,040,392**
Indirect Employment Revenues	
Coal-Related Personal Income Tax	$65,177,691
Coal-Related Sales and Use Tax	33,346,726
Coal-Related General State Property Tax	12,927,160
Coal-Related Motor Vehicle Taxes (excluding extended weight decals)	30,057,785
Subtotal	**$141,509,362**
Total Revenues	**$527,722,502**

Figure 15: Total Revenues

The same revenue streams resulting from direct employment in the coal industry comprise the impacts of employment indirectly attributable to the coal industry. Assuming the same average effective tax rate of 4.3 percent of Kentucky Adjusted Gross Income and using the data available, we estimate Kentucky's state revenue from personal income taxes paid by those employed in jobs indirectly attributable to the coal industry to be $65 million. Using the same methods as in the direct employment section, we estimate $33 million in sales tax revenue, $13 million from general state property tax, and $30 million in motor vehicle taxes including fuel tax. We estimate that indirect employment attributable to the coal industry generates $142 million in state tax revenue, bringing the total state revenue attributable to the industry to $528 million.

Indirect Employment Expenditures

The people employed as an indirect impact of the coal industry's work in the state provide significant revenue, but the state must also spend money to support these people by providing schools, roads and other services. We use the same method to estimate indirect expenditures that we used to determine the share of state expenditures to support those directly employed by the industry. Those employed as an indirect effect of the industry's presence comprise 2.6 percent of state employment in 2006. We subtract state spending to support the coal industry from the general and road fund expenditures and find that 2.6 percent of remaining expenditures is $215 million, bringing total state expenditures associated with the presence of coal in the state to nearly $643 million.

Direct Industry Expenditures	**($355,221,108)**
Direct Employment Expenditures	**(73,140,605)**
Indirect Employment Expenditures	
State Expenditures to Support Citizens Employed as an Indirect Result of the Coal Industry's Presence	**($214,192,262)**
Total Direct and Indirect Expenditures	**–$642,553,975**

Figure 16: Total Expenditures

In this model those indirectly employed as a function of the industry's presence cost the state more than those employed by the industry and they fail to cover their costs in the taxes they pay to the state. This discrepancy is due to the comparatively lower wages of indirect and induced jobs.

The estimates presented here suggest that while direct employment in coal by itself is a net benefit both to those employed and to the state of Kentucky, this benefit comes at a significant cost. The industry itself costs the state more than the industry contributes to public funds and the indirect employment impact, while important, is concentrated in lower wage work such that we do not see a net increase in state revenue. These findings are important, but they still overlook several key elements of the cost of the industry to the citizens of Kentucky.

Omitted Variables and Updates

The Impact of Coal on the Kentucky State Budget is not a comprehensive discussion of the effects of the industry on our state's budget or on economic activity in the state. The externalized costs of the industry should be part of any full discussion of energy and economic development strategies for the Commonwealth. In the case of coal, these costs include but are not limited to healthcare, lost productivity resulting from injury and health impacts, water treatment, water infrastructure to replace damaged wells, environmental remediation, limited development potential due to poor air quality, pollution control, and social spending associated with declines in coal employment and related economic hardships of coalfield communities.

Recent studies indicate links between coal production and combustion and rates of illness and mortality. Michael Hendryx of West Virginia University finds that even when controlling for other factors such as smoking, poverty, education, rural-urban setting, race, ethnicity and other variables, mortality rates increase when coal production increases from one to seven million tons.[62] In another study, Hendryx and his colleagues found that the odds of hospitalization for chronic obstructive pulmonary disease (COPD) and hypertension increased with increases in coal production.[63] A recent study from Johns Hopkins Bloomberg School of Public Health links levels of arsenic in drinking water to higher rates of diabetes. Arsenic can get into drinking water naturally, but is also a pollutant from coal burning and copper smelting.[64] According to the Clean Air Task Force, coal-fired power plants are to blame for higher child asthma rates among those living within a 30 mile radius of coal-fired power plants.[65] The health impacts of coal production and use cost the state in healthcare spending and lost productivity.

In addition, the extended weight coal haul system adds costs not accounted for here. The trucking of coal and the damage to roads in communities throughout the eastern and western coalfields affect health, environment and quality of life for those living on and near the 4,000 miles of road used to haul coal throughout the state. The 1980 LRC study noted that "continuous dust, noise and vibration, for instance, may cause a higher incidence of disease among those living along deteriorated coal haul roads. Coal trucks traveling at high speeds along narrow roads are a safety hazard, as is the broken, rutted pavement of damaged roads."[66] The 1995 KTC study of the extended weight coal haul road system noted that while the higher weights have not caused a significant increase in accidents involving coal trucks, they have caused an increase in the proportion of accidents that involve injuries or fatalities. According to a *Lexington Herald-Leader* analysis, "At least 53 people died and 536 were injured in accidents with trucks licensed to haul coal from 2000 through August 2004."[67]

We also do not address workers' compensation expenditures in this report because the Workers' Compensation Funding Commission (KWCFC) is not funded through the state general fund, but by employer payments to workers' compensation. The Labor Office handles workers' claims and the state workers' compensation program. According to the *Kentucky Office of Workers' Claims 2006-2007 Annual Report*, 14.09 percent of worker claims in 2007 came from the mining industry. We have no reason to believe that mining's share of claims would be significantly different for fiscal year 2006.

These figures represent significant improvements in mine safety over the last 30 years, but mining remains a dangerous occupation. The state established the KWCFC in 1987 to develop a stable funding plan for retiring various liabilities under the state's workers' compensation program. At that time, an assessment was imposed on workers' compensation premiums paid by all employers, including those engaged in the severing or processing of coal. Due to the higher level of liability related to the coal industry, an additional assessment was imposed on the workers' comp premiums received from coal operators. These funds were placed in the "Special Fund" for workers' compensation liabilities. In the early years, the coal rate was as high as 48.9 percent (1994) and came down to 24.0 percent by 1996.[68] In 1996, new legislation (*KRS 342.122*) replaced the additional assessment on coal operators with the specific allocation of $19 million in coal severance tax revenues to the Special Fund. However, due to general fund deficits, state budgets have excluded transfers of coal severance funds to the KWCFC since FY 2002.[69]

Black Lung is covered under a separate workers' compensation fund. In 1996 the Coal Workers' Pneumoconiosis Fund (CWPF) was created (*KRS 342.1242*) to provide benefits for claims based on exposure to coal dust and incurred after December 12, 1996. At that time, assessments were imposed on both coal employers and the severance of coal on a calendar year basis. Revenues from these assessments are restricted to the CWPF. For FY 2006, an annual assessment of 0.50% was imposed on workers' compensation premiums of employers engaged in the severance or

mining of coal, with an additional assessment of $0.025 per ton of coal severed by every such entity. No coal assessments were imposed in 2008 and 2009, as there is sufficient money in the CWPF to pay all claims.[70] Conversations with attorneys working on Black Lung claims suggest that changes in workers' compensation criteria in the state have reduced successful claims in recent years. Unable to receive reimbursements from the state, many miners end up filing for compensation funds available through a federal Black Lung fund.

In addition to omitted variables, the state has established additional tax expenditures and benefits to the coal industry since 2006. In the area of education, the state established a $200,000 per year scholarship fund for the University of Kentucky Mining Engineering program. As the result of the enactment of HB1 during the August 2007 General Assembly Special Session, the coal industry will benefit from additional incentives in the coming years. The bill includes tax incentives for construction of alternative fuel or gasification facilities. The Office of the State Budget Director expects this incentive to result in foregone revenue of $21.3 million in 2010 alone. In addition, coal purchased for an alternative energy (liquid fuel) or gasification facility will be subject to an exemption "equal to eighty percent of the severance taxes paid on the purchase or severance of coal that is specifically used as feedstock for the facility." Because these plants are not expected to be up and running for some time, the *Tax Expenditure Analysis 2008-2010* does not show dollar estimates for these expenditures.

Our estimates provide a rough sketch for understanding the easily counted costs and benefits of the coal industry to the state budget. The omission of numerous externalities, federally funded supports and more recent additions to tax expenditures suggest that our work provides only a small piece of a far more complex relationship between the state and the coal industry. A comprehensive analysis of this relationship would include attention to these complexities and would more fully represent the costs of the industry to the state and its future prospects for sustainable development.

Conclusions and Policy Implications

The Impact of Coal on the Kentucky State Budget provides estimates of the revenues and expenditures attributable to coal in the Kentucky state budget. According to this analysis, the industry provides an estimated $528 million in state revenue, with the coal severance tax making up over 40 percent of that revenue. But those revenues do not offset the expenditures associated with hosting the industry. Based on our estimates, the state spends nearly $643 million on coal-related infrastructure, regulation, tax preferences, research, training and other expenses for an annual net fiscal impact of –$115 million.

The analysis presented here is necessarily based on several assumptions and estimates. A precise analysis of the fiscal impact of an entire industry is impossible to construct. This report does not attempt to quantify and monetize the costs often referred to as externalities, including the industry's impact on health and environmental quality. However, the approach used here improves upon unsubstantiated speculation of the industry's impact as well as assessments that only focus on coal's benefits. The findings shed light on the role of the coal industry in our state and thereby raise important questions about the state's energy, economic development and fiscal policies.

When MACED released its 1986 study of coal in Kentucky, over 39,000 Kentuckians worked in the industry. By 2006, coal employment had declined 54 percent to just under 18,000 workers. Now, as then, technological changes are reducing the demand for labor while new and ongoing environmental concerns raise serious questions about the viability of coal as a future source of energy. Today, carbon dioxide comprises 84.5 percent of U.S. greenhouse gas emissions and fossil fuel combustion is the primary source of these emissions.[71] As the climate impact of a warming planet becomes more apparent, support for regulations to reduce climate-changing emissions grows.

The longstanding historic trends in the coal industry in Kentucky, combined with the reality of a rapidly changing energy landscape, pose challenges to the long-term role of coal as a provider of employment and source of tax revenue for Kentucky. In light of this reality, Kentuckians are engaged in serious discussion about what kind of energy policy state government should support. At the same time, ongoing budget problems plague the state due to a structural imbalance between the growth of revenues and expenditures. Appalachian Kentucky's coal field communities are among the most distressed in the country while the Commonwealth as a whole ranks 44th among the states in per capita personal income; a position Kentucky has occupied since 1970.[72] The Commonwealth faces serious fiscal, economic development and energy choices.

The Impact of Coal on the Kentucky State Budget suggests three key recommendations as we move forward:

- **Compare future investments in coal to investments in energy alternatives.**
  The state launched a period of more active energy policy with the recent passage of House Bill 1 in a 2007 special session, House Bill 2 in the 2008 General Assembly and the release of Governor Beshear's new energy plan. Kentucky invests modestly in renewable energy and energy efficiency, while it aggressively pursues policies to support coal and invest in new coal technologies. As the nation and the world begin to reduce dependence on fossil fuels, the Commonwealth must make strategic energy choices based on the full costs and benefits of the options before us.

- **Pursue economic diversification.**
  As this report indicates, the costs associated with hosting the coal industry are significant. The long-term downward trend in coal employment and the approaching end of low coal-fired electricity prices further diminish the industry's economic development benefits. While no one knows for sure how long coal will be mined in Kentucky, it is not a renewable resource. We must work harder to achieve lasting economic diversification throughout Kentucky and its coalfield communities.

- **Examine the way coal is taxed and subsidized in the state.**
  While the coal severance tax is often referenced for its contributions to Kentucky communities and the state budget, its benefits are diminished when the costs associated with hosting the coal industry are more fully represented. At the same time, tax expenditures for the coal industry are a set of growing but largely hidden subsidies that reduce revenue to the state budget. Taxation theory suggests higher taxes on activities, like the mining of coal, which cannot be relocated to other states. But the Commonwealth has not adjusted several coal-related taxes and fees in many years.[73] Kentucky should examine its rate of taxation and use of subsidies and think strategically about the needs of the Commonwealth and the best path to a prosperous future.

Technical Appendix: Estimating Coal Haul Road System Costs

The coal haul road system has long been the subject of study and concern. This system consists of rural roads, state highways and interstates that facilitate the transport of coal from mine mouth to tipple, train, barge and power plant. These roads withstand tremendous wear and tear and require frequent extensive maintenance. The coal haul road system includes county and local roads as well as state maintained roadways. The estimates that follow reflect only those costs for state-maintained roads in the coal haul system.

In September 1980, the Kentucky Legislative Research Commission (LRC) released *The Fiscal Impact of the Kentucky Coal Industry*. That report used existing data and models to provide four estimates of the cost of the coal haul road system. The LRC presented models that ranged from a very conservative estimate of maintenance costs to a far larger estimate incorporating the annual share of long term construction, maintenance and repair costs. Here we will review the LRC study as well as several more recent analyses of highway cost allocation and the extended weight coal haul road system to arrive at a series of estimates of the coal industry's share of road construction and maintenance expenditures for 2006.

The Commonwealth builds and maintains 96 percent of the roads that comprise the coal haul road system; the other four percent are maintained by county and local governments.[74] The state designates road segments as coal haul roads based on self-report usage data. Within the coal haul road system, road segments carrying loads of more than 50,000 tons of coal in the previous reporting year are designated extended weight and require an extended weight decal for trucks carrying more than 90,000 pounds. Roads in coal producing counties carried 1,577,501,793 ton-miles of coal haul activity in 2006 while coal impacted counties (counties that have roads that are part of the coal haul road system, but that do not produce coal) carried 141,849,747 ton-miles of coal haul activity.[75] The total state coal haul system in 2006 bore 1,719,351,540 ton-miles of coal hauling. The coal haul system covered 3859 miles (3744 on state-maintained roads)[76] of roadway with 2,602 miles comprising the extended weight system.

"The total mileage of highways used to haul coal in Kentucky has declined since the mid-1980s, as has the mileage eligible for the extended-weight system. This occurred at the same time that the total ton-miles for coal transported by highway increased."[77] This suggests that

while total mileage impacted by the industry has decreased since the cost studies of the late 1970s and 1980s, damage on those roads that comprise the system is likely more intense as a result of heavier loads traveling fewer miles of road.

A central element driving increased load size per truck is the 1987 establishment of the extended weight coal haul system. Buttressed by a drive to keep Kentucky coal competitive and ensure that drivers did not feel the need to break the law in order to make a living, the General Assembly chose to legalize excessively heavy coal loads through the extended weight coal haul decal system. Coal haulers are able to purchase an extended weight decal that allows them to travel on the extended weight coal haul road system carrying loads that exceed 80,000 pounds and that often reach as much as 120,000 pounds. In 1995, KTC reported that approximately two-thirds of trucks with extended weight decals registered in the 120,000 pound category.[78] KTC conducted an analysis of data from weigh stations focusing on the types of trucks that are allowed to operate with increased weight limits. They found that "a relatively small percentage of the vehicles exceeded the limits. On US 23 in Boyd County, there were 186 trucks (10.4 percent of the total trucks) which exceeded the extended-weight limits."[79] The Boyd County weigh station was the only site that had more than 10 percent of trucks exceeding the weight limits.

In the 1995 KTC study of the extended weight decal and haul system, researchers estimated annual pavement overlay costs for the extended weight system at around $9 million higher than they would be with previous weight limits enforced. If we adjust the $9 million from 1993 dollars to 2006 dollars we estimate pavement overlay costs at around $12.56 million above what they would be if the extended weights were not allowed (heavier weights increase maintenance requirements). Overlay costs are only a portion of total expenditures for the coal haul roads. The 1995 KTC study concludes that the extended-weight system is a "subsidy of the movement of Kentucky coal by the road users throughout the state."[80] The extended weight decal system caused a significant decline in Truck Permit registrations costing the state more than what it collects in decal revenue.

Coal trucks are not the only road users that fail to cover their costs. The problem of user responsibility for incurred costs is endemic to the road system. In the late 1990's the KTC estimated that pickups and vans, light trucks and medium trucks more than covered their road costs in registration fees and taxes. Cars, heavy trucks and buses all fell short of paying the full cost of their road use. While evasion occurs, the problem is more accurately described as a market failure resulting from the public nature of road use.

Roads are public goods. "Roads are not sold; their use is open to all (except, of course, in the case of a few remaining toll roads."[81] This non-exclusion constraint means that market signals do not appropriately apportion costs for the roads without intervention. Some revenues are collected for road use by coal trucks, but the "amounts are rarely adequate to defray road maintenance expenses. Ultimately, the use of general public funds becomes inevitable."[82] Portions of the direct costs associated with road use by the coal industry become externalities not incorporated into the cost of coal and not collected from the coal industry by the public entities that maintain the roads (the state as well as local and county governments). In effect, Kentucky tax payers subsidize kilowatt-hours fueled by Kentucky coal for utility users in nearly two dozen states and beyond U.S. borders. This dynamic is unfortunate, but also difficult to avoid without far more administrative and regulatory expense. The phenomena is not unique to coal, but rather a common problem, particularly for natural resources. All the same, it must be included in our understanding of the benefits and costs of the industry to the state.

Given the need for the state to provide public use roads, researchers develop methods for estimating cost allocation within the state road system. Without exact figures for road construction, maintenance and enforcement expenditures for coal haul roads and extended weight coal haul roads, it is difficult to provide concrete figures on the cost of these roads. The 1980 LRC study provides some key characteristics of road costs to keep in mind as we try to attribute costs to a particular industry[83]:

- *The use of public roads is not limited to one class of vehicle. The total cost of maintaining coal roads cannot be assessed against the coal industry (costs must be apportioned).*
- *The deterioration of roads, or the need for better roads, due to heavy traffic, imposes a demand for public funds. This cost can be deferred by the responsible agency. The choice to defer costs often results in social costs in the form of longer travel times, lower property values and vehicle damage.*
- *The demand for better roads, imposed by heavy truck use, could be met in several ways: by increased maintenance of existing roads, by construction and maintenance of heavy duty gravel roads, by construction of hard-surface roads*

capable of withstanding heavy use. The costs of alternatives differ, and the choice of alternatives can bias the resulting estimate.

Road costs, cost allocation estimates for the coal haul road system, and tax responsibility calculations for motor carriers are based on self report data, making them vulnerable to underreporting and evasion. Anecdotal evidence, as well as discrepancies between expected and collected revenues, suggests that coal haul mileage is underreported.[84]

One of the greatest obstacles to accuracy in cost allocation studies is the method by which the weight and axle configuration distribution among trucks traveling in Kentucky is determined. Studies base these estimates on "a sample of Kentucky trucks involved in reportable traffic crashes." This sampling technique assumes that coal trucks involved in traffic accidents accurately represent the distribution of weight and axle characteristics of the population of coal trucks operating in the state.

Moreover, traditional methods for road maintenance planning assume a useful service life of 20 years. In a 1983 Kentucky Energy Cabinet study, *The Impact of the Coal Industry on Kentucky's Economy*, John D. Abell notes, "This and other assumptions are really only valid if the coal trucks manage to meet the proper weight requirements."[85] A. R. Romine, assistant state highway engineer for operations was quoted in the Courier Journal in 1979, "The effect of illegal (overweight) vehicles on the (state) highway program has been catastrophic. And it's getting worse. It's beyond our means to maintain a hard-surface road...in eastern Kentucky under those kinds of axle loads."[86] MACED (1986) points out that in the same news article, the director of the Division of Research at the Department of Transportation noted that one particular eastern Kentucky road designed to last 20 years had to be replaced after two years because of increased truck traffic. This observation is confirmed in the 1980 LRC study, "a pavement designed to handle truck traffic at the rate of one hundred 80,000 pound 5-axle semi-trailer trucks a day over a 20-year period will require substantial renovation after 2.4 years if used daily by one hundred such trucks weighing 120,000 pounds each."[87] If we assume that heavier trucks simply mean fewer loads to carry the same amount of coal, these figures still suggest that a 20-year road will need substantial renovation in four years.

Deferred costs, long term road plans and projects, and the methods by which some road work is funded mean that examining one year's numbers can mask costs as well as changing dynamics of the coal haul system and usage. A study of travel activity, vehicle types and loads from 1994 to 2005 offers a narrative for understanding the changing dynamics of road use and impact attributable to the coal industry. A series of regression models based on road type indicates that the total number of trucks on rural roads in the state declined while the proportion of those trucks classified as heavy/coal increased. Coal trucks with fewer axles became more prevalent at the same time that weights increased. Heavier weights on fewer axles, and particularly in the straight trucks most prevalent for coal haul use, cause more damage to road surfaces than the same weight spread across more axles or distributed in the trailer truck configuration. A six-axle, single trailer truck is the preferred configuration, but straight trucks remain common. While fewer trucks and a decline in the mileage comprising the coal haul road system might sound like a recipe for lowering costs, it is not clear that this is the actual impact.

Given the difficulties of accurately measuring road use, damages and cost allocation, we will present several models that produce varied estimates of the coal industry's share of annual road costs. Each model has problems. The first estimate updates the 1980 study published by the Kentucky Legislative Research Commission (LRC) and is based on a weighted average of four distinct cost allocation models. The second estimate adjusts MACED's 1986 figures to account for inflation. The MACED study was written by Richard Sims, an economist who was a primary author on the 1980 LRC study. The MACED estimate is the highest of our estimates as it reflects a very high level of deferred costs and projections for the cost of reducing the backlog. The state of Kentucky made investments to reduce this backlog during the 1980's and the coal haul road system is in better shape today than it was then. With this in mind, we acknowledge that this estimate is high, but we present it as a reminder that continued wear adds to the costs each year and that work done in the 1980's is now 20 years old. Between 1996 and 2003, the state spent $110 million to resurface U.S. 23.[88] On a road system as large and well-used as the coal haul road system there will always be mileage in need of significant reconstruction. The final set of calculations reflects more recent work on cost allocation and the extended weight system combined with assumptions found in early work on the issue. All of these estimates are based on assumptions and incomplete data, but the relative consistency of the estimates suggests that the cost of the coal haul road system to the state of Kentucky is significant.

To provide context for understanding coal haul road numbers, it is helpful to have some sense of how much it costs to do standard road work. Road maintenance and

reconstruction costs vary based on the extent of the damage and the standard to which roads must be built or reconstructed. Thin overlay costs are roughly $132,000 per mile of four-lane roadway; thick overlay is roughly five times larger and ranges in cost with an average of $661,420 per mile of four-lane roadway.[89] Coal haul roads must be built to carry weights over 80,000 pounds so their costs tend to be high.

Another way to provide some general sense of a base level to work from is to simply use what we know about general maintenance (this is simply crack filling, joint work and patches) and spread costs by miles (not vehicle miles traveled or axle loads). We compose an algebraic equation that assumes that costs are spread evenly across state mileage with coal haul road system costs averaging $397 per mile more for annual maintenance (KTC's 1995 figure of $300 per mile in coal counties adjusted for inflation). Accounting for debt service on coal road projects and state support to counties for maintenance of coal roads, this method suggests that based strictly on mileage and slightly higher basic maintenance costs, one could estimate coal's share of road fund expenditures at around $188 million. This figure does not account for variation in vehicle miles traveled, axle loads and associated frequent repair or the need to construct to higher standards. The model also does not account for deferred maintenance and long-term needs. We know this is not how monies are dispersed and that this estimate is too low, but it provides a base from which to understand coal haul road costs. This calculation suggests that estimates of state expenditures on the coal haul road system in the range of $200–$300 million per year are reasonable.

Legislative Research Commission 1980

Given the complexity of the road revenues and expenditures, one option for estimating the cost of the coal haul road system is to simply update the careful and inclusive study conducted by the LRC in 1980. The LRC hedged against overly conservative and overly generous estimates by using the mean of four estimates. The first estimate cited in the LRC study includes only maintenance costs for the coal haul road system and attributes 75% of those costs to the coal industry without accounting for accelerated deterioration on coal roads. Maintenance generally refers to joint repair and filling chips and potholes. This model estimates total costs of $ 28,030,500 ($99,313,690 in 2006 dollars). The second estimate assumes that all primary and secondary roads in the coal regions must be built to accommodate 80,000 pound loads. The model assumes these upgrades would be unnecessary without the coal industry and so subtracts an estimate of general repair costs from the estimated cost to improve roads to accommodate coal trucks and then adds an annual construction cost amount to reflect the added damage that would be done in the year in question. This model estimates total costs at $32,417,650 in 1976 dollars ($114,857,610 in 2006 dollars).

Estimate number three contains projections for total construction costs without added damage of the coal industry and subtracts that from total estimated reconstruction costs given the expected traffic patterns of the coal industry. The model estimates total costs at $31,229,800 ($110,648,990 in 2006 dollars). The final estimate presented in the LRC study includes construction, maintenance and reconstruction costs and assumes that the existing design of roads and shoulders would be sufficient if the roads carried no coal at all. Under that scenario, roads would need to be restored to existing design standards not intended to accommodate heavy loads. Estimate number four is quite high, $153,422,850 ($543,586,060 in 2006 dollars). The LRC admits that this estimate is likely too high, but also suggests that the other three estimates are too low. With this in mind, they took a weighted average that lent greater weight to estimates one and two and arrived at a total cost increment for the coal industry of $51.4 million.

If we simply adjust $51.4 million (1976) for inflation, the LRC models estimate total costs of $182.11 million. Simply updating the LRC estimate to reflect inflation accounts for increases in a variety of costs since 1976 (the data year for the 1980 study), but fails to account for other changes such as significant road construction that occurred in the 1980's; the passage and implementation of the extended weight decal system which increased the number of trucks carrying excessively heavy loads, while decreasing the overall number of trucks; and a decline in the number of mines and accompanying decrease in total mileage covered by the coal haul road system—a shift that shrinks the total road area subjected to coal haul wear, but may increase the severity of damage on the more concentrated coal haul road system.

MACED 1986

MACED updated figures from a 1983 Kentucky Energy Cabinet (KEC) report, *The Impact of the Coal Industry on Kentucky's Economy* (the most comprehensive estimate used in the LRC study) to arrive at an estimated cost of $243.8 million for 1985. The KEC model (authored by John D. Abell) considered only the 1,501 miles of road in coal counties rated as below adequate. The model did not include the 18.5 percent of coal roads not in coal-producing counties, nor did it include any maintenance costs for the 4,500 miles

of road in the coal haul system that rated adequate. KEC assumed that upgrades would cost $2 million per mile and that half of the upgraded roads would have a useful service life of 20 years and half 15 years before major improvements would be needed. Abell noted that service life assumptions were only valid if trucks met proper weight requirements. Based on a sense that these service life estimates were overstated, MACED adjusted the service life numbers to 17 years and 12 years. When we adjust for inflation, MACED's 1985 estimate totals $456.8 million for FY 2006.

More recent figures on construction, reconstruction, repair and maintenance costs suggest that the $2 million figure is high, but if you plan on standard annual maintenance plus construction, reconstruction and bridge work throughout the coal haul road system as well as work to accommodate increased weight limits in the extended weight system, then these figures look reasonable.

Heavy Trucks And Cost Increments For FY 2006

Pavement construction, reconstruction and repair are expensive and even more so when roads must meet specifications for carrying heavy trucks. The Kentucky Transportation Center (1995) reports overlay costs of $100,000 ($132,280) per mile for a four-lane roadway and an average $500,000 ($661,420 in 2006 dollars) per mile for thicker overlays. Even roads that do not require pavement overlays will still require annual maintenance including crack and joint filling, patching, chip sealing and pothole repair. Costs for annual maintenance are also higher in coal producing areas than in the rest of the state (an average $397 higher per mile). [90]

The extended weight (EW) system adds costs above and beyond the already higher costs resulting from coal truck damage throughout coal producing and impacted counties. The Kentucky Transportation Center estimates that a full one third of the added expense associated with the EW system are attributable to overweight trucks' (decaled or not) use of the base system (meaning roads in coal producing and impacted counties that are not designated as part of the EW system). This is not surprising as EW roads are not necessarily connected to one another in a continuous system and roads are not designated as EW until after state records indicate more than 50,000 tons of coal transport in a year. In other words, EW trucks do not just travel on the EW system.

An ideal overlay rotation would have the state placing new overlay on one-fourth of the coal haul road system each year. To support loads over 80,000 pounds, the coal haul road system requires thicker overlays than other roads. If we apply the average cost of $661,420 per mile of four-lane road to the coal haul road system, assuming that two lane roads cost about half as much (though they are likely to require significant should work), then with 82.2 percent[91] of coal haul road miles as two-lane rural roads and the other 17.8 percent of coal haul road miles as four-lane roads, the total estimated cost is around $364.6 million. If 75 percent of these costs are attributable to coal (based on Abell's estimate), then we can attribute $273.5 million in 2006 dollars to the coal industry for FY 2006. This scenario is based strictly on cost and some estimate of likely need for the road work based on coal truck activity and damage data. But we know that the state is likely to use less expensive maintenance to help defer costs to a later date. Subsequent models are based on actual road spending for FY 2006 and are more likely to reflect state budget constraints and the decision to defer costs. Keep in mind, however, that any year's expenditures will include some expenses that were deferred in prior years.

The remaining models use vehicle miles traveled (VMT) as a multiplier for cost allocation. VMT covers some of the added costs associated with higher traffic on these roads than would be there without the coal industry, but do not incorporate the difference between one mile of coal truck travel and one mile of passenger car travel. Heavy trucks cause significant damage to roads whether they are coal trucks or not. The extended weight exception to weight limits means that coal trucks carry heavier loads than other trucks and their wear and tear tends to be geographically concentrated. The types of trucks and axle configurations of many coal trucks cause more damage than the large five or six axle trailer trucks that traverse the interstates with heavy loads of consumer goods. These trucks no doubt cause significant damage, but their travel patterns more often include federally maintained portions of the interstate system and more axles mean a better distribution of weight to reduce impact on the roads. The axle loads of straight trucks, often traversing mountainous rural roads in the coalfields, have a disproportionate impact on state costs.

The KTC found that the extended weight coal haul road system carried 19% of vehicle miles traveled (VMT) on state maintained roads. As noted, use of VMT for cost allocation is somewhat problematic in that it assumes that road impact and damages are spread proportionately across the state maintained road system based on miles traveled. Coal haul trucks incur a level of damage that exceeds their share of vehicle miles traveled. Equivalent axle loads for coal

trucks in 2006 varied from 2.275 to 4.299 per axle with number of axles ranging from three to six. Usually the larger number of axles leads to a smaller equivalent axle load as the weight burden is distributed across the road. Smaller trucks with fewer axles tend to have higher axle loads and cause more damage.

Even though the miles of road in the coal haul road system have declined as have the number of mines, the amount of coal transported remains high. Fewer trucks are doing the work and are often carrying heavier loads, but the reduction in number of trucks and miles of road does not lower the burden on the roads. Concentrated hauling of heavier loads means similar levels of damage and demand for road construction, reconstruction and repair. In addition, the extended weight system generates significant demand for bridge reconstruction as many of the bridges in the EW system are not built to carry 80,000 pound loads, much less 120,000 pound or heavier loads. A bridge built for 50,000 pound loads may be sandwiched between two segments of road built to an 80,000 pound standard.

These problems aside, if we use VMT as a crude estimator and extrapolate out to include the entire coal haul road system and we account for somewhat lower traffic on non-EW coal haul roads (we use KTC figures for coal county base system traffic) these roads carry roughly 23.9 percent of travel on state maintained roads. Using VMT to determine a share of costs that assumes administrative, capital and maintenance costs vary by VMT without regard to vehicle weights, the coal haul road system is responsible for $273.6 million of spending in the FY 2006 state budget. Following on earlier studies, we estimate that 75 percent of road costs on roads that carry coal are attributable to coal hauling (given that coal hauling can reduce service life from 20 years to two to four years, this seems like a reasonable estimate). Using this method, we estimate coal's share of maintenance costs on the coal haul road system to be $205.2 million.

This estimate represents a reasonable estimate of many road-related costs. However, the method underestimates capital expenditures for grade, drain, surfacing and resurfacing work and maintenance and operations spending on structures.[92] Without definitive information on axle configurations for the 3,000-4,000 coal trucks operating in the state and the mileage and payload of those trucks, it is difficult to arrive at accurate cost allocation estimates. These complexities are exacerbated by the fact that we know that many trucks underreport activity or operate off the radar altogether.

In addition, expenditures specific to the Resource Recovery Road System include a state allocation of $1,003,000 to the counties to help cover costs associated with county maintained roads that are part of the coal haul road system and $38,838,600 in Debt Service for prior construction on the Resource Recovery System. If we take these funds out of the road fund before calculating coal's share of remaining road fund expenses and then add them back in on top of the coal industry's share of all other expenses, then we attribute $237.9 to the presence of the coal industry.

State record-keeping and the inherent limits to regulatory control and monitoring mean that we cannot provide precise figures on the coal industry's share of road expenses to support their use of the roads for hauling coal and equipment. Our purpose is to provide some information that sheds light on the range of costs associated with the industry's presence so that we might better assess the state's role in supporting the industry.

The coal haul road system was subject to a lot of discussion in the late 1970's and 1980's and the extended weight system and cost allocation modeling are addressed in periodic studies commissioned by the state and completed by the Kentucky Transportation Center. This work is very helpful in understanding the components of road expenses and the complexity of determining sound methods for cost allocation without complete information. Given the myriad issues surrounding cost allocation, we thought it best to follow the LRC's (1980) lead and provide a few estimates pointing out the distinct strengths and weaknesses of each. If we take the average of the three models above (model one based on regular thick overlay rotation, model two based on VMT and model three including VMT and debt service and support for county maintenance of coal roads), we arrive at an estimated coal haul road cost of $238.9 million for FY 2006.[93]

Endnotes

1 Jepsen, Christopher, Kenneth Sanford and Kenneth R. Troske. 2008. "Economic Growth in Kentucky: Why Does Kentucky Lag Behind the Rest of the South?" Lexington, KY: Center for Business and Economic Research.

2 US Census Bureau. 2007 Poverty and Median Income Estimates – Counties.

3 Cheves, John. 2009. "Coal Tax Won't Take a Hike." *Lexington Herald-Leader* (May 6): A1.

4 We use the fiscal year 2006 severance tax revenue figure presented in the state "General Fund Detailed Revenue Estimate" of the Consensus Forecasting Group (CFG) for January 31, 2007. *The Budget of the Commonwealth 2006-2008* reported figures from the 2005 Consensus Forecast for their Severance Tax break downs and their coal severance tax revenue figure was $215,687,000. *Kentucky Coal Facts 2007-2008* reported 2006 coal severance tax revenues of $221,416,062. The CFG figure of $224 million should be the most recent and therefore most accurate reflection of actual collections for FY 2006. These funds do not all go into the General Fund. For 2006, the state used $1,318,500 for the Osteopathic Medicine Scholarship Program (KRS 164.7891) and $1,000,000 went to the Trover Clinic. The state set aside $19 million for Workers' Compensation in the General Fund. Remaining funds totaled $203,171,611, of which 50% is returned to coal producing and impacted counties through the Local Government Economic Assistance Fund and the Local Government Economic Development Fund. A total $101,585,806 should have been distributed through these programs. We do not address local and county revenues and expenditures associated with coal in this report so the details of these disbursements are not included. Coal Severance Revenues remaining in the General Fund totaled $120,585,806. We count all of the severance tax revenue funds in our calculations and do not include disbursements from the coal severance tax as expenditures. If we include only those revenues that remain in the General Fund after disbursements, then the net impact of coal revenues and expenditures on the general and road fund budgets is –$217,952,595.

5 Kentucky Office of Energy Policy Division of Fossil Fuels & Utility Services and the Kentucky Coal Association. *Kentucky Coal Facts 2007-2008*, 10th edition. Frankfort, Kentucky: Commonwealth of Kentucky and the Kentucky Coal Association, p. 15. *http://www.kentuckycoal.org/documents/CoalFacts08.pdf*. This represents an average collection of 84.5% of the amount due.

6 The coal industry does not own many buildings in the Commonwealth, but they do pay taxes on mining equipment. We were unable to obtain industry level figures for property tax revenue. Coal-related state property tax revenues (except the unmined minerals tax) were estimated on the assumption that property taxes are proportionate to coal's share of employment in the state. This means that revenues from the industry's property taxes (except unmined minerals taxes) are reflected in the property tax figures that appear in the Direct Employment section of the report.

7 Office of State Budget Director. *2006-2008 Budget of the Commonwealth*, Volume 1, p. 27.

8 *Kentucky Coal Facts 2007-2008*, p. 15.

9 *Kentucky Revised Statutes*, 177.9771."Extended weight coal or coal by-products haul road system."

10 *KRS* 186.050 (3).

11 Calculations of truck registration revenue are based on the number of trucks that purchased extended weight decals, the extended weight registration fee and Kentucky Transportation Cabinet estimates of the portion of trucks paying full registration, the portion paying partial and the percent of miles logged in Kentucky for those registered in multiple states. The Kentucky Transportation Cabinet provided these estimates via e-mail correspondence with the author.

12 *KRS* 177.9771.

13 The figure for extended weight decal revenue comes from the Kentucky Transportation Cabinet. 2008. E-mail to author, September 30. The amount is slightly higher than that reported in the Road Fund Revenue Estimate of January 31, 2007. The discrepancy simply reflects that the numbers were not final at the time of the CFG report. The Consensus Forecasting Group. 2007. "Road Fund Revenue Estimate," January 31.

14 Pigman, Jerry G., Joseph D. Crabtree, Kenneth R. Agent, R. Clark Graves and John A. Deacon. 1995. *Impacts of the Extended-Weight Coal Haul Road System*. Frankfort, KY: Kentucky Transportation Cabinet.

15 Data limitations make it difficult for us to isolate fuel and vehicle tax revenues from the coal industry. We know that coal trucks, particularly large ones, are able to take advantage of some exemptions, but we are unable to be more precise in our estimates. We follow the method used in MACED's 1986 study and estimate coal's total share (corporate and coal employment) as proportionate to coal employment as a share of total state employment.

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17 Thompson, et al. 1996, p. 10.

18 Consensus Forecasting Group. 1/31/2007. *General Fund Detailed Revenue Estimate*. The revenue estimate for fiscal years 07 and 08 reports actual revenue for FY 2005-2006.

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20 *Kentucky Coal Facts 2007-2008*, p. 16.

21 Sims, Richard. 1986. *A Public Sector Income Statement for the Coal Industry in Kentucky, 1985-2000*. Berea, KY: MACED. Sims (1986) used a profit margin of 3.4 percent as reported for 1984 coal industry profits in *Forbes* magazine. A 199.

22 Corporate income tax in Kentucky varies for different portions of a firms income. During FY 2006 for those subject to standard corporate income tax, the entity must pay the greater of the following:4% of the first $50,000 of taxable net income; 5% of taxable net income over fifty thousand dollars up to $100,000; and 7% of taxable net income over one hundred thousand dollars; or "an alternative minimum calculation of an amount equal to the lesser of the amount computed under" a subsequent section of KRS 141.040

23 Office of the State Budget Director. *Tax Expenditure Analysis: Fiscal Years 2008-2010,* p. 21.

24 *KRS* 139.480 (2) as cited in Office of the State Budget Director. Tax Expenditure Analysis: Fiscal Years 2006-2008. Frankfort, KY: Commonwealth of Kentucky, p. 136.

25 *Tax Expenditure Analysis: Fiscal Years 2006-2008*, p. 136.

26 U.S. Department of Energy, Energy Information Administration. "Kentucky State Energy Profile," 2006 data. Retrieved 08/13/2008 (http://tonto.eia.doe.gov/state/state_energy_profiles.cfm?sid=KY).

27 *KRS* 141.010(12)(d)

28 *KRS* 141.041, effective 1984 as summarized by the Office of the State Budget Director in the *Tax Expenditure Analysis 2008-2010*.

29 *KRS* 141.0405, effective 2000.

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31 KRS 143.010(6)(11), effective 1978 as cited in *Tax Expenditure Analysis Fiscal Years 2006-2008*, p. 50.

32 This figure excludes the sales tax exemption for residential utilities and the Energy and Energy Producing Fuels exemption that is shared among fuel sources (though mostly benefitting coal), but includes the coal severance tax expenditures.

33 "Policy Note," *Budget of the Commonwealth 2006-2008*, Volume 1, pp. 70-71.

34 In addition to the General Fund monies that we include, the following restricted funds are appropriated in support of the industry:

Included in the Budget of the Commonwealth *is $3.5 million in Restricted Funds in each year of fiscal biennium 2006-2008 for research grants. These funds will originate from the Local Government Economic Development Fund Multi-county Fund (coal severance tax). The General Assembly directed this money to be used for research projects relating to clean coal, new combustion technology, thin-seam coal extraction research, synthetic natural gas produced from coal through gasification processes, and the development of alternative transportation fuels produced by processes that convert coal or biomass resources or extract oil from oil shale and shall be targeted solely to Kentucky's Local Government Economic Development Fund-eligible counties.* "Policy Note," *Budget of the Commonwealth 2006-2008,* Volume 1, pp. 70-71.

35 "Policy Note." *Budget of the Commonwealth 2006-2008*, Volume 1, pp. 70-71.

36 These numbers were provided by the Provost Budget Office at the University of Kentucky via e-mail correspondence.

37 Pigman et al. 1995, p. 31.

38 Abell, John D. 1983. *The Impact of the Coal Industry on Kentucky's Economy*. Frankfort, KY: Kentucky Energy Cabinet, September.

39 We used the 2007 coal haul data (reporting on 2006 activity) to determine what portion of the coal haul roads are two-lane and what portion are four-lane. We coded all Kentucky and US highways as two-lane and all interstates and parkways as four-lane. Based on mileage per road segment, we found that 82.2 percent of coal haul road mileage is two-lane roads and 17.8 percent is four-lane.

40 *Kentucky Coal Facts 2007-2008*, p. 12. Using total production data along with employment data, we estimate that the industry provides an additional 234 jobs in those counties for which employment is not reported to protect the privacy of individuals and companies.

Note: Mining employment figures provided by the Kentucky Coal Facts report do not include those employed in administrative and professional services in Lexington and Louisville and our calculations based on production do not address these missing data.

41 *Kentucky Coal Facts 2007-2008*, p.12.

42 Labor force and employment data for 2006 come from The U.S. Department of Labor Bureau of Labor Statistics Annual Averages (http://www.bls.gov/lau/#tables), "Labor force data by county."

43 *Kentucky Coal Facts 2007-2008*, p. 10. Note: Employment number is slightly larger on page 10. We will use the number on which wage figures are based for the sake of consistency. The larger figure may reflect some of the employment that is not included in the wage data for proprietary reasons. Counties with less than three employers or one employer with 80% of the total county miner workforce were withheld to avoid disclosure of individual company data. These counties include: Boyle, Clark, Elliott, Fayette, Greenup, Hancock, Jackson, Jefferson, Lee, McCreary, McLean, Mason, Ohio and Pulaski. *Coal Facts* report authors suspect that multi-county mining employment contributes to some counties being under reported and others being over reported. We found production data for 2006 for additional counties not mentioned in *Kentucky Coal Facts 2007-2008*. The U.S. Department of Energy, Energy Information Administration reported coal production in 2006 in Christian, Morgan and Owsley counties.

44 Population Division, U.S. Census Bureau. *Table 1: Estimates of the Population by Selected Age Groups for the United States and States and for Puerto Rico: July 1, 2006 (SC-EST2006-01)*, released May 17, 2007.

45 For this report, coal producing counties are defined as those that reported coal severance tax revenues for fiscal year 2006 as presented in *Kentucky Coal Facts, 2007-2008*, 10th edition.

46 If we use coal counties that paid severance tax in FY 2006-2007, then the percentage of the population employed directly in coal is 1.87. If we use counties that report employment or production or are named as counties where production occurred, but data are not published for proprietary reasons, then those employed in mining comprise 1.61 percent of the population.

47 *Kentucky Coal Facts 2007-2008*, p. 10. Coal county designation determined by coal severance tax revenues by county. Calculations of total working age population by county based on data from the Population Division, U.S. Census Bureau. *County Characteristics Resident Population Estimates*. Retrieved 08/20/08 (http://www.census.gov/popest/counties/asrh/CC-EST2007-agesex.html).

48 Direct impact as reported in *Kentucky Coal Facts 2007-2008*.

49 In an attempt to account for those counties excluded from employment and wage data (as noted above), we use county and state level production data along with available wage and employment data to calculate likely aggregate wages and employment for the excluded counties.

50 Output numbers appear to reflect value of total production for 2006—there is no reason to believe that any output data are excluded from this aggregate figure so it requires no adjustment.

51 *Kentucky Coal Facts: 2007-2008 Pocket Guide*, p.12. *http://www.kentuckycoal.org/documents/CoalFacts08.pdf*.

52 *KY Coal Facts 2007-2008* reports $1,034,834,951 in total wages for 25 coal producing counties. Counties with less than three employers or one employer with 80% of the total county miner workforce were withheld to avoid disclosure of individual company data. These counties are as follows: Boyle, Clark, Elliott, Fayette, Greenup, Hancock, Jackson, Jefferson, Lee, McCreary, McClean, Mason, Ohio, and Pulaski. Based on calculations of income by output for included counties and total output for the state, we estimate total earnings of$1,048,533,659. Note: Direct mining employment does not include most of the administrative/professional employees of coal companies located in Kentucky's metropolitan areas of Fayette and Jefferson counties and does not include private services.

53 With 17,669 people employed and a total of $1,034,834,951 paid in wages by the mining industry, average wages are roughly $58,000 per year. *Kentucky Coal Facts: 2007-2008*.

54 Institute on Taxation and Economic Policy. February 2005. *The ITEP Guide to Fair State and Local Taxes*. Washington, D.C.: ITEP, p. 12.

55 Office of Employment and Training. May 2008. "2006 Kentucky Total and Nonwhite Population and Labor Force Data by County." Frankfort, KY: Commonwealth of Kentucky. Retrieved 10/13/2008. (http://www.workforcekentucky.ky.gov/admin/uploadedPublications/340_2006_Total_and_NonWhite.pdf). See endnote 6 for an explanation of industry inclusion in the state property tax figures.

56 In keeping with the models used in *Kentucky Coal Facts 2007-2008*, we use the RIMS II (Regional Impact Modeling System) multipliers for the Appalachian Coal Industry.

57 Thompson et al. 1996. Dr. Charles Haywood updates the figures for the annual *Kentucky Coal Facts* report.

58 Direct impact as reported in *Kentucky Coal Facts 2007*.

59 In an attempt to account for those counties excluded from employment and wage data (as noted above), we use county and state level production data along with available wage and employment data to calculate likely aggregate wages and employment for the excluded counties.

60 Output numbers appear to reflect value of total production for 2006—there is no reason to believe that any output data are excluded from this aggregate figure so it requires no adjustment.

61 *KY Coal Facts* reports $1,034,834,951 in total wages for 25 coal producing counties. Counties with less than three employers or one employer with 80% of the total county miner workforce were withheld to avoid disclosure of individual company data. These counties are as follows: Boyle, Clark, Elliott, Fayette, Greenup, Hancock, Jackson, Jefferson, Lee, McCreary, McClean, Mason, Ohio, and Pulaski. Based on calculations of income by output for included counties and total output for the state, we estimate total earnings of$1,048,533,659. Note: Direct mining employment does not include most of the administrative/professional employees of coal companies located in Kentucky's metropolitan areas of Fayette and Jefferson counties and does not include private services.

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Uncertainty and Variability in Health-Related Damages from Coal-Fired Power Plants in the United States

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The health-related damages associated with emissions from coal-fired power plants can vary greatly across facilities as a function of plant, site, and population characteristics, but the degree of variability and the contributing factors have not been formally evaluated. In this study, we modeled the monetized damages associated with 407 coal-fired power plants in the United States, focusing on premature mortality from fine particulate matter ($PM_{2.5}$). We applied a reduced-form chemistry-transport model accounting for primary $PM_{2.5}$ emissions and the influence of sulfur dioxide (SO_2) and nitrogen oxide (NO_x) emissions on secondary particulate formation. Outputs were linked with a concentration-response function for $PM_{2.5}$-related mortality that incorporated nonlinearities and model uncertainty. We valued mortality with a value of statistical life approach, characterizing and propagating uncertainties in all model elements. At the median of the plant-specific uncertainty distributions, damages across plants ranged from \$30,000 to \$500,000 per ton of $PM_{2.5}$, \$6,000 to \$50,000 per ton of SO_2, \$500 to \$15,000 per ton of NO_x, and \$0.02 to \$1.57 per kilowatt-hour of electricity generated. Variability in damages per ton of emissions was almost entirely explained by population exposure per unit emissions (intake fraction), which itself was related to atmospheric conditions and the population size at various distances from the power plant. Variability in damages per kilowatt-hour was highly correlated with SO_2 emissions, related to fuel and control technology characteristics, but was also correlated with atmospheric conditions and population size at various distances. Our findings emphasize that control strategies that consider variability in damages across facilities would yield more efficient outcomes.

KEY WORDS: Externalities; fine particulate matter; power plants; variability

1. INTRODUCTION

Analyses of health-related damages of power plant emissions have generally used complex chemistry-transport models to characterize the relationship between emissions and population exposures. Because of time constraints within a policy context, these models often either focus on a small number of individual power plants in a defined geographic area with a model such as CALPUFF[1–6] or a large number of power plants simultaneously with a model such as the Community Multiscale Air Quality (CMAQ) model.[7] Although these more complex models capture atmospheric fate and transport well, the outputs provide limited insight about differences in health-related damages across power plants. Thus, it is unclear the degree to which results from one setting are transferable to another setting, or whether control strategies that effectively treat emissions from all sources identically are suboptimal.

Recently, studies have addressed the question of variability among damage estimates using less complex chemistry-transport models. One study[8]

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used reduced-form state-by-state source-receptor (S-R) relationships to capture the effects of nitrogen oxide (NO_x) and sulfur dioxide (SO_2) emissions on secondary fine particulate matter ($PM_{2.5}$) concentrations, providing estimates of benefits per ton of SO_2 reduction by state. However, there can be substantial variability across power plants within states, and there were no formal attempts to determine why marginal damages per ton varied between states. Similarly, two other studies applied a county-resolution S-R matrix across the United States,[9,10] but one study only considered urban-rural differences in marginal damages[9] while the second study[10] used individual power plant marginal damage values only to structure and compare national control strategies. Aside from omitting characterization of variability in marginal damage estimates across individual power plants, none of these studies formally considered uncertainty associated with application of a reduced-form chemistry-transport model or considered how that uncertainty would compare with uncertainties in other assumptions underlying the marginal damage estimates.

In principle, a number of factors could contribute to variability in marginal damages per ton of emissions or per unit electricity generation across power plants, even when considering only one type of fuel. Using the example of coal, there may be differences in combustion technologies, control technologies, or the sulfur or ash content of the coal. Stack characteristics and meteorological factors will influence fate and transport, including the rate of formation of secondary byproducts. The size of the population downwind of the power plant will influence the population exposures per unit emissions, and nonlinearities and/or thresholds in the concentration-response functions will influence the health risk per unit exposures. Moreover, many of these factors contain significant uncertainties, some of which may differ by plant type and geographic location.

While all of these factors are theoretically influential, it is unclear which would be dominant or what the magnitude of variability in marginal damages across power plants would be. A literature review reported marginal damages per unit electricity generation for coal-fired power plants that spanned three orders of magnitude across studies,[11] but could only attribute variability to methodological aspects of the studies (e.g., use of abatement cost vs. bottom-up vs. top-down approaches) and lacked the data needed to evaluate characteristics of the site or facility. Another study that focused on interpreting the differences in externality estimates between two large-scale models[12] demonstrated that site characteristics, such as population size and background concentrations, could contribute to differences in findings, but only compared two sites and did not formally address the numerous site and source differences.

In this study, we estimate the marginal damages associated with mortality from exposure to $PM_{2.5}$ for 407 coal-fired power plants in the United States. While other pollutants and pathways contribute to damages, previous studies have shown that $PM_{2.5}$-related mortality is the dominant contributor to monetized damages from power plant emissions[7] or air pollution in general.[9,13] We use a county-resolution S-R matrix to characterize the effect of plant-specific emissions of $PM_{2.5}$ and particle precursors (NO_x and SO_2) on population exposures. We compare with other chemistry-transport models to estimate uncertainty, and apply newly developed concentration-response functions for the relationship between $PM_{2.5}$ and premature mortality, using statistical techniques to account for potential nonlinearities and for uncertainties in the concentration-response function. We use a regression modeling approach to explore the heterogeneity in plant-specific damage estimates and determine the factors that best explain this heterogeneity. To our knowledge, this is the first attempt to examine the degree of heterogeneity in marginal damages across a large number of power plants within a country or to formally determine the dominant contributors to that heterogeneity.

2. METHODS

Given our focus on the $PM_{2.5}$-related health effects of power plant coal combustion, we first determine emissions of $PM_{2.5}$ and particle precursors as well as plant characteristics for a number of power plants in the United States. We then present a model linking emissions with ambient concentrations, including characterization of baseline concentrations and the marginal influence of individual power plants on $PM_{2.5}$ concentrations, and with comparison to published values to provide a first-order approximation of model uncertainty. We describe the statistical approach to account for uncertainties in the relationship between $PM_{2.5}$ exposure and premature mortality, including the possibility of thresholds or nonlinearities. We provide an estimate for the economic value of a statistical life, considering evidence of the time lag between changes in concentrations

and health outcomes. We conclude by discussing our statistical approach for combining uncertainty distributions and the regression modeling framework we use to explore variability in damage estimates across power plants.

2.1. Emissions and Plant Characterization

Although there are numerous power-generating facilities in the United States, we focused on coal-fired power plants that had been incorporated previously into a S-R matrix (Section 2.2). For these plants, we gathered data from the Emissions and Generation Resource Integrated Database (eGRID)[14] and the National Emission Inventory (NEI).[15] eGRID included information on NO_x and SO_2 emissions, as well as plant location, fuel type, heat input, electricity generation, and other plant characteristics. The NEI database was used to estimate primary $PM_{2.5}$ emissions. In both cases, we used data from 1999 to ensure internal consistency, given available data at the time of our analysis. Of note, for combined heat and power facilities, we use only those emissions associated with electricity generation, excluding those related to useful thermal output (as not all damages from these facilities should be exclusively assigned to electricity outputs).

We gathered additional data to help explain variability in marginal damage estimates within the regression modeling described in Section 2.6. This included information at the boiler or unit level about the presence of control devices, which we used to estimate the percentage of the power plant electricity generation (proxied by heat input of the boiler) with controls for SO_2, NO_x, or $PM_{2.5}$. We considered both presence/absence of controls as well as control technology type for SO_2 (wet scrubber vs. dry scrubber vs. other) and NO_x (combustion modification vs. add-on control vs. other). We used boiler-level data to determine the percentage of generation not required to meet New Source Performance Standards based on a database provided by the U.S. EPA (Bryan Hubbell, personal communication, April 2008), and also calculated the percentage of the electricity generation brought online prior to 1970. We additionally gathered information on sulfur and ash content of the coal.[16]

Given this pooled data set, we excluded power plants where coal was not the primary fuel, where emissions data or S-R matrix outputs were unavailable for any of the three pollutants, or where the power plant had been deactivated before 1999. Of the 507 power plants included in the S-R matrix, 414 were active and primarily fueled by coal, and 7 of these plants lacked S-R matrix outputs for one of the three pollutants. Thus, the resulting database included 407 power plants (Fig. 1), with total estimated emissions in 1999 of approximately 11.7 million tons of SO_2, 5.0 million tons of NO_x, and 600,000 tons of primary $PM_{2.5}$. These plants may not be representative of the array of coal-fired power plants across the United States, but they emitted over 90% of national

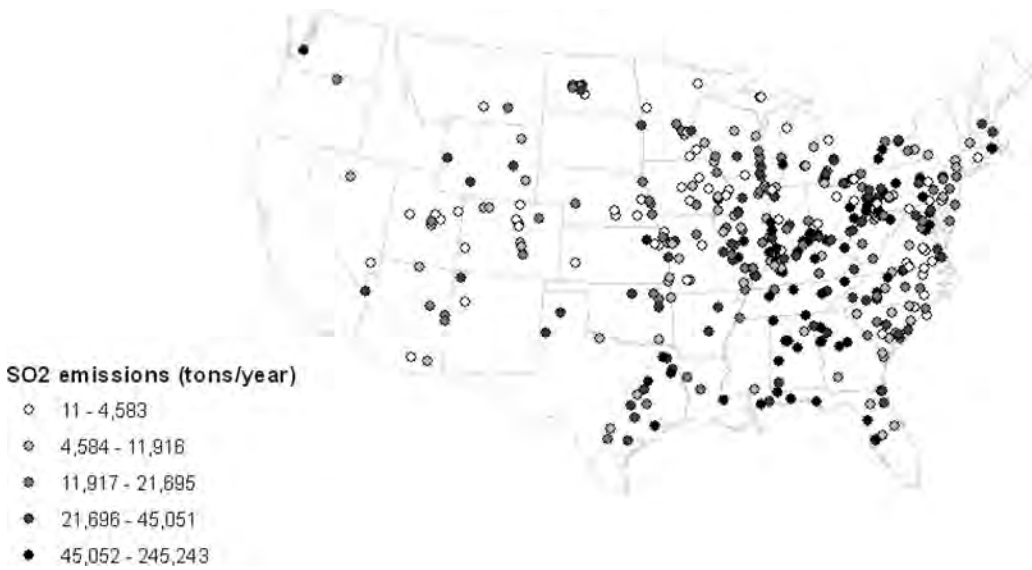

Fig. 1. Location of 407 coal-fired power plants and their annual emissions in 1999 of SO_2 by quintile.

power plant emissions of SO_2 and $PM_{2.5}$ and over 80% of national power plant emissions of NO_x in 1999.

For the uncertainty propagation, we assume that the emissions of SO_2 and NO_x are effectively known without uncertainty (or, in reality, with uncertainty small in magnitude relative to other components of the model). Both of these pollutants are monitored with continuous emissions monitoring systems (CEMS) for power plants within the Acid Rain Program, and are therefore well characterized. For the 407 plants in our study, only 1% of emissions of SO_2 and NO_x are estimated without any CEMS data. For primary $PM_{2.5}$, emissions were more often estimated based on plant characteristics and standard emissions factors and are therefore somewhat more uncertain. No data are available to characterize the magnitude of uncertainty, but given previous characterization of the confidence level for these estimates as medium-low (vs. high for SO_2 and NO_x),[17] we presume that primary $PM_{2.5}$ emissions are known within a factor of 2 at each power plant (i.e., characterized with an asymmetric triangular distribution with a minimum of $0.5E$, a mode of E, and a maximum of $2E$, where E is the reported $PM_{2.5}$ emission rate).

2.2. Source-Receptor Matrix

For each power plant, we estimated the relationship between emissions and incremental contribution to ambient concentrations using a S-R matrix. S-R matrix is a reduced-form model based on the Climatological Regional Dispersion Model, a sector-averaged Gaussian dispersion model that includes wet and dry deposition and first-order chemical conversion of SO_2 and NO_x to sulfate and nitrate particles. More detail about the model is available elsewhere.[18–20] While S-R matrix is simplified relative to state-of-the-science chemistry-transport models, models such as CMAQ are computationally impractical for marginal analyses of numerous individual facilities and pollutants (requiring thousands of multi-day runs). Moreover, S-R matrix has been shown to yield similar health impact estimates to CMAQ[10] and CALPUFF,[4] and it includes a calibration step to ensure correspondence with ambient monitoring data. In this step, data from EPA's Federal Reference Method and Speciation Network monitors were spatially interpolated to county centroids, and we used the ratios between these values and the uncalibrated model outputs to develop county-resolution calibration factors. The calibration factors had a median value of 0.9, indicating that relatively little bias was found in initial S-R matrix outputs on average, although there was spatial variability in the calibration factors (5th percentile of 0.5, 95th percentile of 1.4, range of 0.11–3.5). S-R matrix provides output at county resolution, so we use this geographic resolution for the remaining steps in the assessment.

To characterize S-R matrix uncertainties and to develop covariates for our regression models explaining variability in damages, we rely on a summary measure relevant for marginal damage analysis. The intake fraction (iF) indicates the fraction of a pollutant or its precursor that is inhaled by some member of the population.[21] It is defined as:

$$iF_{j,k} = \Sigma_i (P_i \Delta C_{ij}) \frac{BR}{Q_k}, \tag{1}$$

where $iF_{j,k}$ is the intake fraction estimating exposure to pollutant j as a function of emissions of pollutant k (either identical to pollutant j or a precursor of pollutant j), P_i is the population within county i, ΔC_{ij} is the incremental contribution of the source in question to concentrations of pollutant j in county i (μg/m^3), and Q_k (μg/day) is the emissions of pollutant k from the source in question. BR is a nominal population breathing rate, which is generally assumed to be 20 m^3 per day per person; of note, this value divides back out in the damage calculation, and is included so that the intake fractions are unitless values. For the purpose of marginal damage analysis, the quantity $\Sigma_i(P_i \Delta C_{ij})$ is directly proportional to health impacts if the concentration-response function is linear and if baseline mortality or morbidity rates do not vary spatially. Although we use S-R matrix outputs and county-specific mortality rates directly for our marginal damage estimates, we evaluate the degree to which intake fractions explain these estimates.

We estimate four types of intake fractions: iF(p), the impact of primary $PM_{2.5}$ emissions on $PM_{2.5}$ concentrations; iF(as,SO_2), the impact of SO_2 emissions on secondary ammonium sulfate concentrations; iF(an,NO_x), the impact of NO_x emissions on secondary ammonium nitrate concentrations; and iF(an,SO_2), the impact of SO_2 emissions on secondary ammonium nitrate concentrations (due to the fact that ammonium will preferentially react with sulfate over nitrate, implying that SO_2 controls can free up ammonium to react with unneutralized nitrate). Secondary organics and other particle constituents are not included. In addition, although the at-risk population for mortality includes individuals aged 25

and older (Section 2.3), we present intake fractions based on the total population for comparability with other power plant intake fraction publications.[4,22,23] Given correlations between total population intake fractions and intake fractions for individuals aged 25 and older of 0.999 or higher for all four intake fractions, conclusions are unaffected by this choice.

To approximate chemistry-transport modeling uncertainties in a form directly relevant for marginal damage estimates, we compared intake fractions using S-R matrix for 22 power plants in Massachusetts, Illinois, Georgia, and the Washington, D.C. area with intake fractions derived previously for the same power plants using CALPUFF.[1–4] To ensure comparability across models, we used concentration outputs only for counties considered in both models and used identical population data. Across these 22 power plants, the median ratio of intake fractions (S-R matrix divided by CALPUFF) was 0.8 for primary $PM_{2.5}$ (range: 0.4–1.6), 1.0 for secondary sulfate from SO_2 emissions (range: 0.5–1.4), and 0.12 for secondary nitrate from NO_x emissions (range: 0.01–0.45). The ratios did not differ significantly by region for primary $PM_{2.5}$ or secondary sulfate, but were somewhat lower in Massachusetts and the Washington, D.C. area than in other areas for secondary nitrate. However, previous work[4] demonstrated that some of the secondary nitrate differences between S-R matrix and CALPUFF were attributable to insufficient ammonia limitation within CALPUFF, which would tend to increase $iF(\text{an},NO_x)$, and that the effect of this was greatest in the East. Thus, some of the regional differences in the ratios for secondary nitrate may be an artifact of the CALPUFF runs rather than regional bias within S-R matrix.

While it is impossible to infer the magnitude of model uncertainty directly from these data (which compare two uncertain models for a nonrepresentative subset of plants), and the CALPUFF runs did not capture $iF(\text{an},SO_2)$, this comparison gives us the general insight that secondary nitrate intake fractions from S-R matrix will be more uncertain (and perhaps biased as well). We approximate uncertainty by considering our primary $PM_{2.5}$ and secondary sulfate estimates to be accurate within ±50%, with a factor of 3 uncertainty for secondary nitrate. As for primary $PM_{2.5}$ emissions, we characterize these uncertainties using asymmetric triangular distributions (i.e., primary $PM_{2.5}$ and secondary sulfate intake fractions have a minimum of $0.67 * iF$, a mode of iF, and a maximum of $1.5 * iF$, where iF is the intake fraction for a given plant). While this does not allow for values outside of the range listed above, we use triangular distributions to emphasize the somewhat subjective nature of our uncertainty characterization for these terms. Of note, most of the 22 iF ratios fall within a narrower band than the ranges presented above, so our triangular distributions may or may not underestimate uncertainty. In addition, although the degree of uncertainty likely varies geographically as well as by plant within geographic regions, given differential atmospheric chemistry and population patterns, we presume these bounds to be uniformly applicable given insufficient evidence for systematic region-specific or plant-specific uncertainty.

2.3. $PM_{2.5}$-Mortality Relationship

Although multiple publications have established a linkage between $PM_{2.5}$ exposures and premature mortality,[24–26] we build our concentration-response function from a publication[27] that considers nonlinearities in this relationship and allows for characterization of uncertainties related to functional form while addressing questions about the time period in which effects are observed. Briefly, this study fit a number of piecewise linear functions to data from the Harvard Six Cities Study[25,26] with possible slope changes at 10, 15, 20, 25, and 30 $\mu g/m^3$ of annual average $PM_{2.5}$, using Bayesian model averaging approaches to determine the weights placed on each of 32 alternative model forms as a function of how well the model fit the observed data. This study found that a linear model with a central estimate of a 1.2% increase in mortality per $\mu g/m^3$ increase of annual average $PM_{2.5}$ was the most likely model, with a posterior probability of 0.86, but with nonzero probabilities associated with the alternative models.

Within our application, we used model outputs from this study[27] but recalculated some values to fully capture the uncertainties associated with slopes at various background concentrations. First, because the 32 models were fit to the same data, covariance of estimates exists across models. In the publication,[27] the data were divided into 50 groups and jackknife variance estimates were used to capture this covariance, as well as the covariance within model across slope estimates for different pieces. In our application, we computed the jackknife estimate of the slopes and used that as a potentially more robust estimate of the model average results, yielding a function that differed slightly from the main analysis reported in the publication. We characterized uncertainty by considering parametric uncertainty within individual

models as well as uncertainties related to alternative model selection, using jackknife variance estimation to allow for explicit consideration of the covariance across models. In addition, the distributed lag modeling indicated that nearly all of the impacts were observed within 2 years of exposure,[27] which would indicate that the effect of discounting of health outcomes would be minimal.

2.4. Population Data

Given the at-risk population within the epidemiological study described in Section 2.3, we needed to estimate the population and background nonaccidental mortality rates by county for individuals aged 25 and older. We collected population data from the 2000 Census[28] and gathered background mortality data from CDC WONDER,[29] using the average mortality rate from 1999 to 2003 to provide more stable county estimates. No uncertainty is assigned to this model component, and we do not project population counts forward in time, determining damages during the period when emissions data were available.

2.5. Economic Valuation of Premature Mortality

To assign economic values to premature mortality, we use the value of statistical life (VSL) approach, as done within EPA regulatory impact analyses.[7,13,30] Some investigators argue that it is more appropriate in the context of cohort epidemiological studies to estimate loss of life expectancy and assign economic values to life-years rather than lives;[31] however, there is no theoretical rationale for assuming a fixed economic value for a life-year, nor is it evident how age, remaining life expectancy, and other factors should modify the value of a life-year.[32] Empirical studies of age dependence of VSL estimates vary, but are not consistent with a constant value per life-year.[33,34] For these reasons, we focus solely on VSL outputs, noting that our conclusions regarding the degree of variability in health-related damages and the predictive factors are insensitive to this choice.

Recently,[35] U.S. EPA determined a central VSL estimate of $5.5 million (in 1999 dollars) based on 1990 income distributions. This value represented the mean of a normal distribution with a 95% confidence interval between $1 and $10 million, where these confidence bounds represented values drawn from two major meta-analyses. This study also recommended a 3% annual discount rate for mortality in future years and adjustment of VSL for real income growth since 1990. The short lag time between exposure and mortality described in Section 2.3 indicates that discounting will have a minor influence in our analysis. Addressing the latter concern, applying EPA's recommended elasticity value of 0.40[35] to account for per capita real GDP growth from 1990 to 1999 yields a central estimate of approximately $6 million in 1999 dollars. To characterize uncertainty, we scaled the above uncertainty distribution to 1999 dollars, but used a truncated normal distribution to avoid negative VSL and other uninterpretable values. The resulting distribution had a mean of $6 million, standard deviation of $2.4 million, minimum of $1.1 million, and maximum of $11 million.

2.6. Statistical Analyses

We propagated uncertainty across all model components for each power plant by linking Crystal Ball version 7.3.1 (Decisioneering Inc., Denver, CO) to damage calculations made in SAS version 9.1. Of note, some model components (e.g., the VSL) would be applied uniformly to all power plants, with no plant-specific differences. For other model components (e.g., primary $PM_{2.5}$ emissions), the plant-specific uncertainties would not be perfectly correlated with one another, although they would also be unlikely to exhibit perfect independence. While this would complicate our analysis if we were pooling the distributions across plants or statistically comparing the distributions between plants, that is not our objective in this study, so we model plant-specific uncertainties without regard to the potential dependence in the uncertainty distribution between plants, with no impact on our findings.

To determine predictors of variability in damages across power plants, we focused on median estimates from the uncertainty distribution of each plant. By definition, variability in damages per ton of emissions (for SO_2, NO_x, and primary $PM_{2.5}$) would be associated with variability in iF, spatial patterns of baseline mortality rates, and nonlinearities in concentration-response functions. As iF would not be readily available for unstudied power plants, we also investigated variability in iF using population within various radii of the plant as predictors and using a no-intercept linear regression formulation to provide a physically interpretable model. The radii selected for the population terms were based on prior studies explaining variability in iF,[19] for the sake of

comparability, and the final model was determined after removing influential observations (studentized residuals greater than 2). We also explored the possible modifying effect of atmospheric conditions by testing an interaction term reflecting whether the county housing the power plant was nitrate-limited (sufficient ammonium to react with all ambient nitrate) or ammonium-limited.

Variability in damages per kilowatt-hour of electricity generated would be based on variability in damages per ton of emissions and emissions per kilowatt-hour of electricity generated. Although emissions data are available for most power plants, we explore predictors of log-transformed emissions per kilowatt-hour based on plant characteristics (Section 2.1) to help explain variability and to determine candidate variables for subsequent models. We develop these regression models using all-possible-subset modeling, selecting the model with minimum Akaike information criterion (AIC), and remove influential observations prior to final model formulation. The significant variables from the *iF* and emissions models were subsequently considered as candidate variables for models of log-transformed damages per kilowatt-hour, following a similar model-building process.

3. RESULTS

3.1. Distributions and Predictors of Input Parameters

As indicated in Table I, many key input parameters for our analysis vary across the power plants evaluated. Variability is generally highest for emissions, which range widely across power plants for all three pollutants, both in aggregate and per unit heat input. Intake fractions generally have smaller coefficients of variation (COV) than emission rates, especially for SO_2. The *iF* representing population exposure to ammonium sulfate per unit SO_2 emissions varies by a factor of 7 across power plants (COV = 0.322), compared with a factor of 200 (COV = 0.826) for SO_2 emissions per unit heat input.

Examining predictors of emissions per kilowatt-hour, SO_2 emissions were most significantly associated with the percent of electricity generated using bituminous coal, the percent of electricity generation with SO_2 controls, and the sulfur content of the coal (Table II). For NO_x, emissions were most significantly associated with heat input, percent of electricity generation meeting New Source Performance Standards, and the percent of electricity generated using bituminous coal, with less variance explained than for SO_2. For primary $PM_{2.5}$, the percent of electricity generated using bituminous coal was the most significant predictor, with statistical significance for multiple other covariates (Table II). Removal of influential points had a limited influence on regression coefficients or covariates selected; the only statistically significant term in Table II not selected using the full data set was New Source Performance Standard status for SO_2 emissions, which was replaced by age of facility, a covariate capturing a similar construct. The predictors significant for at least one pollutant are carried forward as candidate variables for regression models for damages per kilowatt-hour.

Regression models show that intake fractions are related to population at various distances from the plants (Table III). Population within 100 km of the source only significantly predicts primary

Table I. Distribution of Heat Rate, Emissions, Emissions per Unit Heat Input, and Intake Fractions for 407 Coal-Fired Power Plants in the United States

	Min	25th Percentile	Median	75th Percentile	Max	Coefficient of Variation
Heat rate (MMBTU/kilowatt-hour)	1.59	10.5	11.4	12.1	29.5	0.177
SO_2 emissions (tons/year)	11.4	6,580	17,200	36,500	245,000	1.21
NO_x emissions (tons/year)	8.80	3,420	7,690	17,600	104,000	1.07
$PM_{2.5}$ emissions (tons/year)	0.274	319	779	1,750	12,100	1.27
SO_2 emissions (lb/MMBTU)	0.0293	0.574	0.996	1.73	5.68	0.826
NO_x emissions (lb/MMBTU)	0.056	0.360	0.448	0.613	1.46	0.436
$PM_{2.5}$ emissions (lb/MMBTU)	0.000168	0.0231	0.0413	0.0845	0.513	0.994
iF(p)	3.37E-7	7.34E-7	9.50E-7	1.23E-6	6.28E-6	0.602
iF(as,SO_2)	1.09E-7	2.68E-7	3.36E-7	4.02E-7	7.30E-7	0.322
iF(an,NO_x)	5.38E-9	2.86E-8	5.09E-8	6.61E-8	1.57E-7	0.48
iF(an,SO_2)	−1.52E-7	−5.88E-8	−3.71E-8	−2.87E-8	−5.26E-9	0.551

Table II. Multivariate Regression Models for Emissions of SO_2, NO_x, and Primary $PM_{2.5}$ per Unit Electricity Generated (All Pollutants in Pounds per Kilowatthour)

	SO_2 Coeff. (SE)	NO_x Coeff. (SE)	Primary $PM_{2.5}$ Coeff. (SE)
Intercept	0.30 (0.41)	0.24 (0.36)	−1.5 (0.69)*
Percent of generation with bituminous coal	0.62 (0.066)*	0.15 (0.041)*	0.89 (0.069)*
Percent of generation using coal	1.2 (0.30)*	0.59 (0.16)*	1.6 (0.29)*
Percent sulfur content	4.6 (0.66)*	–	2.9 (0.76)*
Percent ash content	−0.21 (0.11)	−0.14 (0.047)*	0.39 (0.11)*
Percent of generation with SO_2 controls	−0.98 (0.075)*	–	−0.44 (0.079)*
Percent of generation with NO_x controls	−0.22 (0.17)	−0.52 (0.34)	−1.3 (0.73)
Percent of generation with PM controls	0.20 (0.31)	–	–
Heat input (MMBTU/kilowatt-hour)	0.064 (0.020)*	0.11 (0.013)*	–
Percent of generation from boilers built before 1970	–	0.10 (0.054)	0.14 (0.09)
Percent of generation meeting NSPS	−0.16 (0.066)*	−0.15 (0.056)*	−0.25 (0.093)*
Adjusted R^2	0.61	0.32	0.59

*$p < 0.05$.
Note: Covariates included in each model were selected by AIC, and the dependent variables are log-transformed (base e).

Table III. Regression Models Relating Intake Fractions to Population at Various Radii from the Source

	iF(p) Coeff. (SE)	iF(as,SO_2) Coeff. (SE)	iF(an,NO_x) Coeff. (SE)	iF(an,SO_2) Coeff. (SE)
Population within 100 km	6.8E-14* (7.8E-15)	1.0E-17 (2.1E-15)	−5.8E-16 (4.2E-16)	−1.5E-16 (3.2E-16)
Population between 100 and 200 km	4.6E-14* (5.3E-15)	6.6E-15* (1.3E-15)	−2.0E-16 (2.7E-16)	−2.1E-15* (2.2E-16)
Population between 200 and 500 km	6.5E-15* (1.1E-15)	2.5E-15* (2.8E-16)	−2.6E-16* (6.0E-17)	−6.2E-16* (4.8E-17)
Population greater than 500 km	1.9E-15* (1.2E-16)	9.1E-16* (3.2E-17)	2.4E-16* (7.1E-18)	−5.4E-17* (5.5E-18)
Adjusted R^2	0.92	0.94	0.88	0.91

*$p < 0.05$.
Note: Regression models are constructed with no intercept term, as intake fractions must be zero given no exposed populations, so R^2 values should be interpreted with caution.

$PM_{2.5}$ iF, which may be explained by the time needed for secondary formation. The population-based regression model is less interpretable for ammonium nitrate, with only the population greater than 500 km from the power plant displaying statistical significance with a positive coefficient (Table III). This is attributable to the greater importance of atmospheric conditions for secondary nitrate formation, supported by strong spatial patterning of residuals (positive in the Midwest, negative in the Northeast). When an interaction term for source-county atmospheric conditions is introduced, it is insignificant for primary $PM_{2.5}$ intake fractions at all radii, but is significant for iF(as,SO_2) and iF(an,NO_x) at distances beyond 200 km and for iF(an,SO_2) beyond 500 km. As anticipated, power plants in nitrate-limited areas had higher intake fractions for iF(an,NO_x), as they had sufficient ammonium to form secondary ammonium nitrate, and introducing this term reduced the spatial patterning of residuals. The population terms and atmospheric conditions term are carried forward as candidate variables for regression models for damages per kilowatt-hour.

3.2. Distribution and Predictors of Damages per Ton of Emissions

Fig. 2 displays the results of the Monte Carlo analysis for public health damages per ton of emissions of primary $PM_{2.5}$, SO_2, and NO_x, portraying

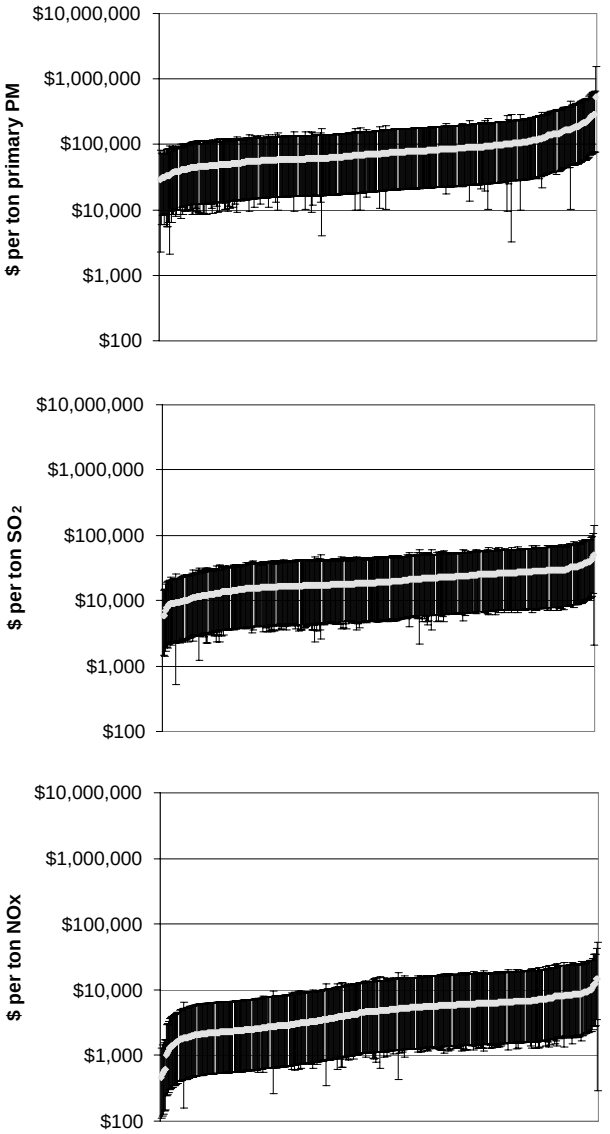

Fig. 2. Public health damages per ton of emissions of primary $PM_{2.5}$, SO_2, and NO_x, sorted by median estimates. Confidence intervals represent the 5th and 95th percentiles for uncertainty around individual power plant damage estimates, the dots represent the median values, and the *y*-axis is on a log scale.

both the uncertainty within individual plant estimates and the variability across power plants. Each pollutant is sorted from minimum to maximum median damage per ton values across plants, but the same plants are not necessarily found at the same point in the variability distribution across pollutants. It should also be noted that, because of the between-plant dependence in many key uncertainties (such as the VSL), overlapping uncertainty distributions should not be interpreted as no significant difference in externalities.

The median estimates of damages per ton demonstrate well-defined patterns of geographic variability (Fig. 3). For primary $PM_{2.5}$, median damages per ton range across plants from approximately \$30,000 to \$500,000 (median across plants of \$72,000, 5th percentile of \$41,000, 95th percentile of \$180,000), with higher values generally found in the industrial Midwest and Northeast. Median damages per ton are highly correlated with the primary $PM_{2.5}$ iF values ($r = 0.99$), indicating a minimal influence of variable background mortality rates or nonlinear concentration-response functions.

For secondary particulate matter (both sulfate formation and nitrate reduction) associated with SO_2 emissions, the median damages per ton range across plants from approximately \$6,000 to \$50,000 (median across plants of \$19,000, 5th percentile of \$10,000, 95th percentile of \$32,000) (Fig. 3). Higher damages are seen in the industrial Midwest, but unlike for primary $PM_{2.5}$, not along the East Coast. As for primary $PM_{2.5}$, the variability in damages per ton is almost entirely associated with iF variability; $r = 0.97$ with the sum of $iF(\text{as},SO_2)$ and $iF(\text{an},SO_2)$.

Finally, for secondary ammonium nitrate associated with NO_x emissions, the median damages per ton range across plants from approximately \$500 to \$15,000 (median across plants of \$4,800, 5th percentile of \$1,800, 95th percentile of \$8,500). In contrast to the other pollutants, the highest values are seen in the Great Plains states of the Midwest (Fig. 3), related to the relatively high ambient ammonia and relatively low ambient sulfate (preconditions for ammonium nitrate formation). As previously, the variability in damages can be explained largely by iF variability ($r = 0.99$).

3.3. Distribution and Predictors of Damages per Kilowatt-Hour Electricity Generated

Median health-related damages from 1999 emissions from 407 coal-fired power plants range from \$0.02 to \$1.57 per kilowatt-hour (median across plants of \$0.14, 5th percentile of \$0.04, 95th percentile of \$0.65) (Fig. 4). The highest values are generally found in the industrial Midwest, although there is some variability within this region and some elevated values in other geographic areas (Fig. 5).

Given that damages per ton of emissions are nearly proportional to iF values, damages per kilowatt-hour can be accurately estimated using

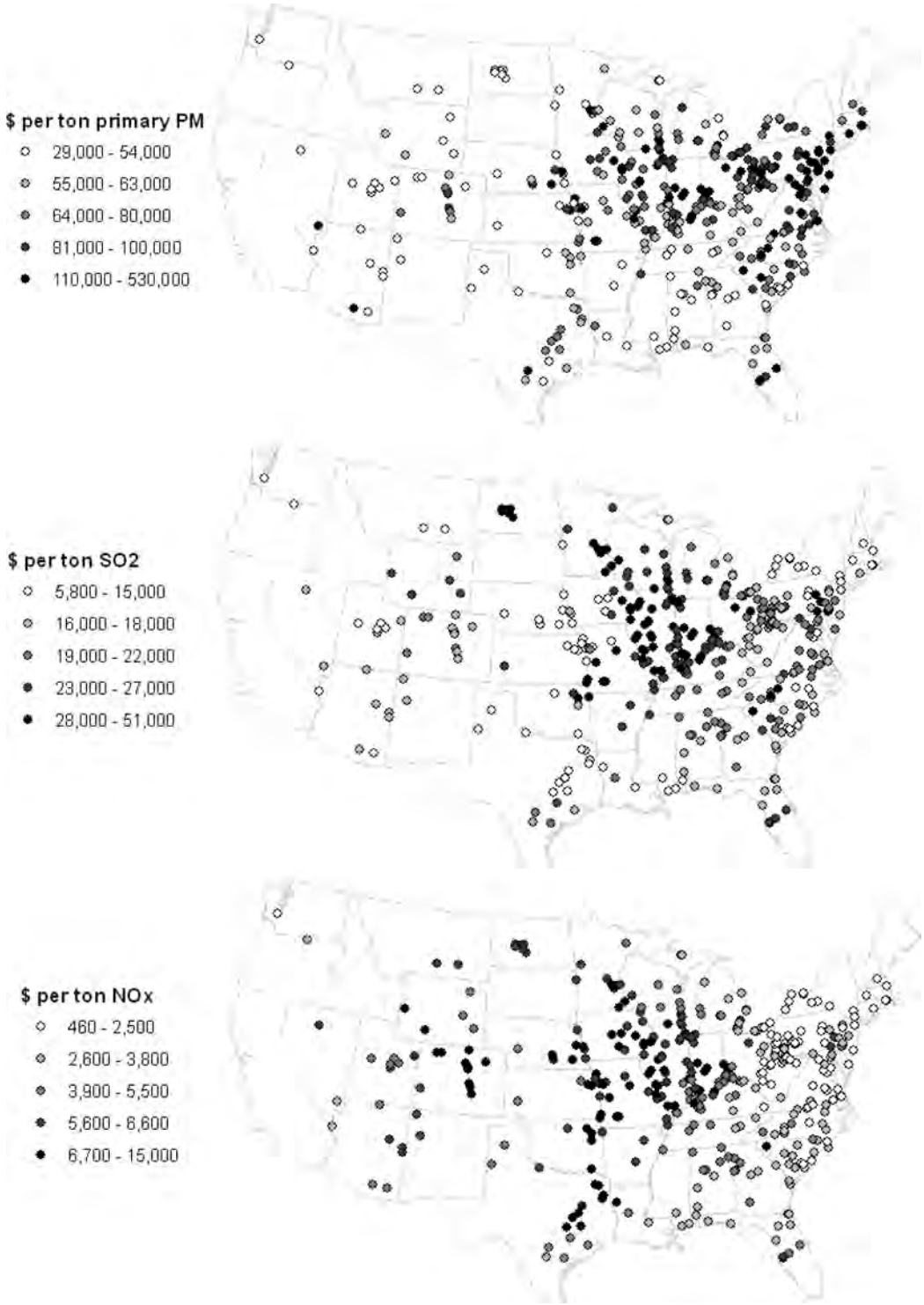

Fig. 3. Median estimates of public health damages per ton of emissions for primary $PM_{2.5}$, SO_2, and NO_x by quintile.

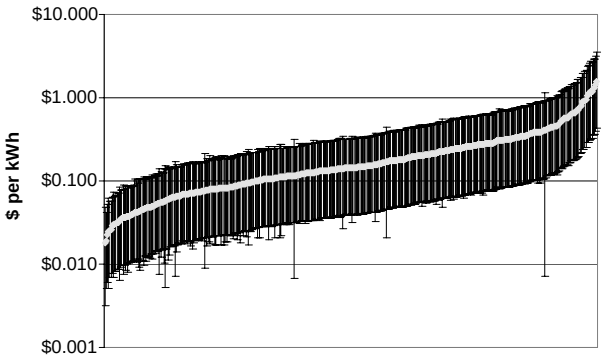

Fig. 4. Public health damages per kilowatt-hour of electricity generation for 407 coal-fired power plants, sorted by median estimates. Confidence intervals represent the 5th and 95th percentiles for uncertainty around individual power plant damage estimates, the dots represent the median values, and the *y*-axis is on a log scale.

emissions per kilowatthour and *iF*. Looking first at univariate correlations prior to constructing multivariate models, damages per kilowatt-hour are highly correlated with emissions of SO_2 per kilowatt-hour ($r = 0.92$), followed by emissions of primary $PM_{2.5}$ per kilowatt-hour (r = 0.83), $iF(\text{as},SO_2)$ ($r = 0.42$), emissions of NO_x per kilowatt-hour ($r = 0.38$), $iF(\text{an},NO_x)$ ($r = 0.26$), and $iF(\text{p})$ ($r = 0.24$). This ordering can be explained by the substantial contribution of secondary sulfate particles to total damages; across power plants, the median percentage contribution to the total damages per kilowatt-hour is 75% for SO_2 (range: 10%–95%), versus median contributions of 14% for primary $PM_{2.5}$ (range: 0.04%–86%) and 8% for NO_x (range: 0.7%–75%). The univariate predictive power of emissions of primary $PM_{2.5}$ per kilowatt-hour is related in part to the positive correlation between primary $PM_{2.5}$ emissions and SO_2 emissions ($r = 0.92$).

Table IV. Multivariate Regression Model for Health-Related Damages per Kilowatt-Hour Electricity Generated, Not Utilizing Intake Fractions or Emissions as Predictors

	Coeff. (SE)
Intercept	−15.5 (3.1)*
Percent of generation with bituminous coal	0.44 (0.072)*
Percent of electricity generated using coal	0.99 (0.26)*
Percent sulfur content	2.7 (0.54)*
Percent of generation with SO_2 controls	−0.48 (0.074)*
Heat input (MMBTU/kilowatt-hour)	0.12 (0.020)*
Percent of generation meeting NSPS	−0.38 (0.065)*
Population between 100 and 200 km	6.6*E*-8 (1.7*E*-8)*
Population between 200 and 500 km	5.2*E*-8 (1.2*E*-8)*
Population greater than 500 km	3.8*E*-8 (1.1*E*-8)*
Nitrate-limited source county	0.24 (0.055)*
Adjusted R^2	0.63

*$p < 0.05$.
Note: Covariates included were selected by AIC, and dependent variable is log-transformed (base e).

Focusing on significant predictors of emissions and intake fractions from Tables II and III to facilitate interpretation of variability, variability in damages per kilowatt-hour is associated with the composition of the coal, percent of electricity generation with SO_2 controls, heat input, percent of electricity generation meeting New Source Performance Standards, size of the population at various distances from the power plants, and atmospheric conditions in the source county (Table IV). All terms

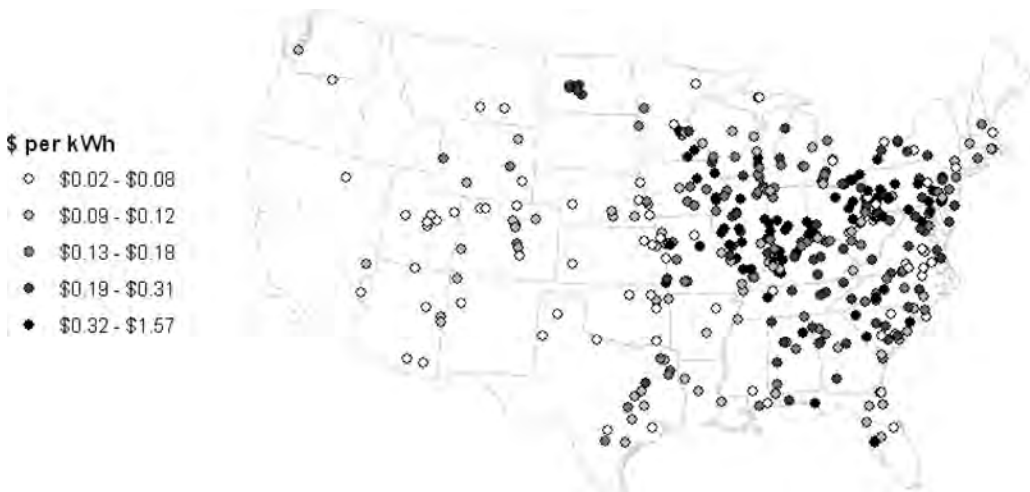

Fig. 5. Median estimates of public health damages per kilowatt-hour of electricity generation for 407 coal-fired power plants by quintile.

are statistically significant and in the anticipated directions, and removal of influential points had a limited influence on regression coefficients and no influence on covariates selected.

4. DISCUSSION AND CONCLUSIONS

Our analysis demonstrates substantial variability in health-related damages per kilowatt-hour generated for 407 coal-fired power plants in the United States, driven in large part by a factor of 200 range in SO_2 emissions per kilowatt-hour across plants. As data about emissions of SO_2 are readily available for most coal-fired power plants, it is tempting to conclude that SO_2 emissions per kilowatt-hour could serve as a direct proxy for damages per kilowatt-hour. However, above and beyond this variability, the population exposure per unit SO_2 emissions varies by a factor of seven across plants, largely related to population size but also associated with meteorological and atmospheric conditions. Thus, even if all power plants had identical control equipment, coal sulfur content, and combustion efficiencies, damages per kilowatt-hour would still vary by nearly an order of magnitude due to differences in exposures per unit emissions. In contrast, the fact that there were minimal nonlinearities in the concentration-response function for mortality associated with $PM_{2.5}$ indicated that this factor contributed little to the overall variability in damages per kilowatt-hour. The large spatial domain over which damages occurred further reduced the influence of nonlinearities in concentration-response functions or spatial variability in baseline mortality rates.

Clearly, there are multiple areas of uncertainty within our analysis, only some of which could be considered in our quantitative uncertainty analysis. For all power plants, our Monte Carlo analyses show that estimates of health-related damages per kilowatt-hour were most sensitive to the VSL and the slope of the concentration-response function for $PM_{2.5}$ at ambient concentrations less than 15 $\mu g/m^3$ (although the covariance among various slope changes complicates apportionment across the concentration-response function). Among the other predictors, the iF for secondary ammonium sulfate was generally the next most significant. In spite of the larger uncertainties for secondary ammonium nitrate formation, it was rarely a significant contributor to overall damage uncertainty, given the general dominance of sulfate relative to nitrate particles for damages from coal-fired power plants.

However, as mentioned previously, S-R matrix is somewhat simplified relative to state-of-the-science chemistry-transport models, and the true uncertainties may not be captured by our relatively simple "factor of X" approximation of model uncertainty (which may itself contribute modest biases, given the assumption that the S-R matrix outputs represent the mode in an asymmetric triangular uncertainty distribution). Moreover, terms like VSL can significantly influence the plant-specific damages per kilowatt-hour but would have no influence on between-plant variability, so our variability conclusions depend significantly on S-R matrix. While S-R matrix did yield similar estimates as CALPUFF for primary $PM_{2.5}$ and secondary sulfate and was calibrated to monitoring data, we did not have data available to formally compare with more advanced models like CMAQ.

We can gain some insight about possible differences between CMAQ and S-R matrix by comparing our aggregate results with those from an analysis using CMAQ for national-scale controls of power plants.[7] This study estimated that removal of approximately 4 million tons of SO_2 and 1.5 million tons of NO_x in the eastern United States would lead to annualized benefits of approximately $100 billion dollars. Applying our median per ton damage estimates for power plants in the same 28-state region as these emission reductions, we determine annualized benefits of approximately $100 billion dollars as well. While there are multiple differences in the underlying calculations (e.g., our concentration-response function is higher, our VSL is slightly lower, and different power plants are included), this indicates that our aggregate estimates are in general agreement with estimates from more advanced chemistry-transport models. However, this comparison does not address plant-specific impacts, and there may be differential uncertainties and biases by region. CMAQ runs for subsets of power plants in different regions would provide insight about this issue and could ultimately allow for more refined regional damage function estimates and more detailed characterization of region-specific uncertainty (potentially even separately estimating different aspects of chemistry-transport model uncertainty).

In terms of the health impacts associated with $PM_{2.5}$ concentrations, we characterized uncertainty within a single epidemiological study, but we did not characterize the uncertainty associated with selecting that study over others. Our reliance on a single study was driven by our desire to formally examine

potential nonlinearities in the concentration-response function with explicit weights on alternative model specifications, which was not available in other publications, but this could contribute additional uncertainties. Past regulatory impact analyses[7,13,30] have generally selected an alternative epidemiological study with a slightly lower concentration-response function (the American Cancer Society cohort). However, a recent study[36] formally elicited expert opinions regarding the magnitude of the concentration-response relationship between long-term $PM_{2.5}$ exposures and mortality risks. Across the 12 experts, their median concentration-response functions ranged from 0.7 to 1.6% decrease in mortality per $\mu g/m^3$ decrease in $PM_{2.5}$ (median of 1.05%), closer to the values used in our study than the values applied previously.

From the perspective of between-plant variability in damages per kilowatt-hour, the magnitude of the concentration-response relationship is immaterial, but the issue of nonlinearities and thresholds is potentially important. However, the American Cancer Society cohort also did not demonstrate deviations from linearity.[24] Within the expert elicitation study,[36] 11 of the 12 experts interviewed believed that there was a lack of empirical and/or theoretical support for a population threshold, with the 12th expert proposing a threshold that was below 5 $\mu g/m^3$ with 80% probability, well below ambient concentrations in most of the United States in 1999. Moreover, most experts supported linear or nearly linear concentration-response functions.

Another key uncertainty not incorporated into our analysis, which could contribute to biases in our conclusions about variability, is the assumption that all forms of $PM_{2.5}$ have equal toxicity. As ammonium sulfate generally dominates the damage estimates, our conclusions could be affected if sulfate particles had either greater or lesser toxicity than average ambient $PM_{2.5}$. While there are clearly uncertainties regarding differential toxicity, elevated sulfate levels have been associated with premature mortality due to long-term exposure,[24] premature mortality due to short-term exposure,[37] and other cardiovascular outcomes,[38–40] with generally similar relative risks as observed for $PM_{2.5}$ as a whole. While modifications to the potency of sulfate particles would clearly influence our damage estimates, it has been concluded that there is currently no specific basis to deviate from a baseline assumption of equal toxicity,[35] so introduction of an uncertain differential toxicity parameter would increase the uncertainty in our estimates but not meaningfully influence our median estimates or our qualitative conclusions about the magnitude of variability in damages per kilowatt-hour.

Our regression modeling also has some clear limitations. Given the data available, the predictors are somewhat simplified. For example, the term addressing ambient concentrations of sulfate/nitrate/ammonium reflected the source county, which does not fully capture the at-risk populations contributing to damage estimates, and the indicator variables for control technologies did not capture many important details. The fact that many predictors are highly correlated with one another complicates interpretation of some models and coefficients. In addition, as we modeled damages for a nonrepresentative set of power plants (generally, higher-emitting plants), the models may not be directly applicable elsewhere. That being said, the models were generally interpretable and reinforced the fact that the size of the population affected by the plume and plant characteristics that influence SO_2 emissions are the primary factors driving damages per kilowatt-hour.

More generally, we have not considered pollutants other than $PM_{2.5}$ or endpoints other than premature mortality, which could influence the magnitude and degree of variability in damages. For example, the omission of ozone-related impacts clearly results in an underestimate of NO_x-related damages. However, it is unlikely that these omissions would change our core conclusion about the presence of significant between-plant variability in damages per kilowatt-hour. We have estimated what prior studies have determined to be the single largest contributor to damages, and most other damages would be positively correlated with the $PM_{2.5}$-related damages (i.e., plants with low combustion efficiency and high emissions will tend to have higher damages across the board). Further study should address between-plant variability in other components of damages, such as ozone, to better establish the degree of heterogeneity.

Finally, it should be recognized that the damage values estimated in our study are not representative of the damages associated with new coal-fired power plants or advanced coal technologies. There is substantial variability in emissions across coal-fired power plants, and plants meeting New Source Performance Standards and/or utilizing emissions control equipment have significantly lower damages per kilowatt-hour. We used 1999 emissions given data limitations beyond this point at the time of our

analysis, so application of our damage values per kilowatt-hour to current or future years would need to take account of changing emissions over time as well as population and income growth. Interpretation of marginal damage estimates may also be complicated by various cap-and-trade programs, which may imply that emissions reductions at one facility are counterbalanced by increases elsewhere. Regardless, our framework and models can be easily adapted to a variety of base years and scenarios and can be used to evaluate the impacts of a number of different control policies.

In spite of these limitations, we can draw some conclusions that are informative for both policy decision making and future analyses. First, damages per ton of emissions vary by an order of magnitude across a subset of coal-fired power plants in the United States for SO_2, NO_x, and $PM_{2.5}$ emissions, with damages per kilowatt-hour varying by two orders of magnitude. This indicates that regulatory strategies that effectively treat emissions as identical regardless of source will be nonoptimal. A previous study[10] estimated that health-optimal emission reductions under a national cap could lead to approximately 2,000 fewer deaths per year relative to a uniform or spatially randomized distribution of emission reductions, and our study is supportive of those findings. In addition, our study both provides per-ton damage values that could be used directly for optimal control strategy development and proxy variables that could be used for unstudied power plants. Knowing emissions and intake fractions can lead to accurate estimates of damages; the former is invariably available for power plants or can be reasonably estimated based on fuel composition and plant characteristics, and the latter can be estimated given geographic location and population data within various radii. In principle, our per-ton damage estimates could even allow for trading between pollutants within a control program, although differential uncertainties related to atmospheric chemistry as well as toxicity may imply that more complex modeling would be required to develop such a program.

Beyond conclusions about variability, our findings can be interpreted in relation to the costs of controlling these pollutants and the cost of electricity in the United States. Within the regulatory impact analysis of the Clean Air Interstate Rule,[7] the U.S. EPA estimated that the marginal cost of this cap-and-trade program would be approximately \$700/ton for SO_2 and \$1,300/ton for NO_x in 2010. Setting aside differences in the base years for the analyses, our median estimates of marginal damages per ton of SO_2 are 1–2 orders of magnitude greater than these control costs, while our median marginal damages per ton of NO_x range from 0.4 to 10 times the control costs (with median marginal damages exceeding \$1,300/ton for 399 of 407 modeled power plants). While this does not capture variability in control costs or benefits other than $PM_{2.5}$-related mortality (which may be particularly important for NO_x), this provides some indication of the relative value of these controls. Given the tightening of the ozone National Ambient Air Quality Standard in March 2008, additional NO_x controls will most likely be necessary, and our data demonstrate the magnitude and degree of variability in the $PM_{2.5}$-related co-benefits of controls. Utilizing information as shown in Fig. 3, coupled with an understanding of ozone-related benefits, would allow for the most cost-effective measures to be implemented.

In terms of the magnitude of health-related damages relative to the cost of electricity, our calculated values are large in comparison with the consumer cost of electricity (an average of \$0.09/kWh for all consumers).[41] If these external costs were internalized, it would have significant ramifications for choices among competing fuels for electricity generation in the United States. In particular, older coal-fired power plants appear uneconomic relative to many renewable technologies when the market price and external costs are combined, although this will differ by area of the country and facility characteristics. The magnitude and variability of health-related damages associated with existing electricity generation technologies should be considered in designing optimal energy policy in the United States and elsewhere.

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Appendix A7. Public Meeting Handouts

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Full cost accounting for the life cycle of coal

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Each stage in the life cycle of coal—extraction, transport, processing, and combustion—generates a waste stream and carries multiple hazards for health and the environment. These costs are external to the coal industry and are thus often considered "externalities." We estimate that the life cycle effects of coal and the waste stream generated are costing the U.S. public a third to over one-half of a trillion dollars annually. Many of these so-called externalities are, moreover, cumulative. Accounting for the damages conservatively doubles to triples the price of electricity from coal per kWh generated, making wind, solar, and other forms of nonfossil fuel power generation, along with investments in efficiency and electricity conservation methods, economically competitive. We focus on Appalachia, though coal is mined in other regions of the United States and is burned throughout the world.

Keywords: coal; environmental impacts; human and wildlife health consequences; carbon capture and storage; climate change

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Introduction

Coal is currently the predominant fuel for electricity generation worldwide. In 2005, coal use generated 7,334 TWh (1 terawatt hour = 1 trillion watt-hours, a measure of power) of electricity, which was then 40% of all electricity worldwide. In 2005, coal-derived electricity was responsible for 7.856 Gt of CO_2 emissions or 30% of all worldwide carbon dioxide (CO_2) emissions, and 72% of CO_2 emissions from power generation (one gigaton = one billion tons; one metric ton = 2,204 pounds.)[1] Non–power-generation uses of coal, including industry (e.g., steel, glass-blowing), transport, residential services, and agriculture, were responsible for another 3.124 Gt of CO_2, bringing coal's total burden of CO_2 emissions to 41% of worldwide CO_2 emissions in 2005.[1]

By 2030, electricity demand worldwide is projected to double (from a 2005 baseline) to 35,384 TWh, an annual increase of 2.7%, with the quantity of electricity generated from coal growing 3.1% per annum to 15,796 TWh.[1] In this same time period, worldwide CO_2 emissions are projected to grow 1.8% per year, to 41.905 Gt, with emissions from the coal-power electricity sector projected to grow 2.3% per year to 13.884 Gt.[1]

In the United States, coal has produced approximately half of the nation's electricity since 1995,[2] and demand for electricity in the United States is projected to grow 1.3% per year from 2005 to 2030, to 5,947 TWh.[1] In this same time period, coal-derived electricity is projected to grow 1.5% per year to 3,148 TWh (assuming no policy changes from the present).[1] Other agencies show similar projections; the U.S. Energy Information Administration (EIA)

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projects that U.S. demand for coal power will grow from 1,934 TWh in 2006 to 2,334 TWh in 2030, or 0.8% growth per year.[3]

To address the impact of coal on the global climate, carbon capture and storage (CCS) has been proposed. The costs of plant construction and the "energy penalty" from CCS, whereby 25–40% more coal would be needed to produce the same amount of energy, would increase the amount of coal mined, transported, processed, and combusted, as well as the waste generated, to produce the same amount of electricity.[1,4] Construction costs, compression, liquefaction and injection technology, new infrastructure, and the energy penalty would nearly double the costs of electricity generation from coal plants using current combustion technology (see Table 2).[5]

Adequate energy planning requires an accurate assessment of coal reserves. The total recoverable reserves of coal worldwide have been estimated to be approximately 929 billion short tons (one short ton = 2,000 pounds).[2] Two-thirds of this is found in four countries: U.S. 28%; Russia 19%; China 14%, and India 7%.[6] In the United States, coal is mined in 25 states.[2] Much of the new mining in Appalachia is projected to come from mountaintop removal (MTR).[2]

Box 1.

Peak Coal?

With 268 billion tons of estimated recoverable reserves (ERR) reported by the U.S. Energy Information Administration (EIA), it is often estimated that the United States has "200 years of coal" supply.[7] However, the EIA has acknowledged that what the EIA terms ERR cannot technically be called "reserves" because they have not been analyzed for profitability of extraction.[7] As a result, the oft-repeated claim of a "200 year supply" of U.S. coal does not appear to be grounded on thorough analysis of economically recoverable coal supplies.

Reviews of existing coal mine lifespan and economic recoverability reveal serious constraints on existing coal production and numerous constraints facing future coal mine expansion. Depending on the resolution of the geologic, economic, legal, and transportation constraints facing future coal mine expansion, the planning horizon for moving beyond coal may be as short as 20–30 years.[8–11]

Recent multi-Hubbert cycle analysis estimates global peak coal production for 2011 and U.S. peak coal production for 2015.[12] The potential of "peak coal" thus raises questions for investments in coal-fired plants and CCS.

Worldwide, China is the chief consumer of coal, burning more than the United States, the European Union, and Japan combined. With worldwide demand for electricity, and oil and natural gas insecurities growing, the price of coal on global markets doubled from March 2007 to March 2008: from \$41 to \$85 per ton.[13] In 2010, it remained in the \$70+/ton range.

Coal burning produces one and a half times the CO_2 emissions of oil combustion and twice that from burning natural gas (for an equal amount of energy produced). The process of converting coal-to-liquid (not addressed in this study) and burning that liquid fuel produces especially high levels of CO_2 emissions.[13] The waste of energy due to inefficiencies is also enormous. Energy specialist Amory Lovins estimates that after mining, processing, transporting and burning coal, and transmitting the electricity, only about 3% of the energy in the coal is used in incandescent light bulbs.[14]

Thus, in the United States in 2005, coal produced 50% of the nation's electricity but 81% of the CO_2 emissions.[1] For 2030, coal is projected to produce 53% of U.S. power and 85% of the U.S. CO_2 emissions from electricity generation. None of these figures includes the additional life cycle greenhouse gas (GHG) emissions from coal, including methane from coal mines, emissions from coal transport, other GHG emissions (e.g., particulates or black carbon), and carbon and nitrous oxide (N_2O) emissions from land transformation in the case of MTR coal mining.

Coal mining and combustion releases many more chemicals than those responsible for climate forcing. Coal also contains mercury, lead, cadmium, arsenic, manganese, beryllium, chromium, and other toxic, and carcinogenic substances. Coal crushing, processing, and washing releases tons of particulate matter and chemicals on an annual basis and contaminates water, harming community public health and ecological systems.[15–19] Coal combustion also results in emissions of NO_x, sulfur dioxide (SO_2),

the particulates PM_{10} and $PM_{2.5}$, and mercury; all of which negatively affect air quality and public health.[20–23]

In addition, 70% of rail traffic in the United States is dedicated to shipping coal, and rail transport is associated with accidents and deaths.[20] If coal use were to be expanded, land and transport infrastructure would be further stressed.

Summary of methods

Life cycle analysis, examining all stages in using a resource, is central to the full cost accounting needed to guide public policy and private investment. A previous study examined the life cycle stages of oil, but without systematic quantification.[24] This paper is intended to advance understanding of the measurable, quantifiable, and qualitative costs of coal.

In order to rigorously examine these different damage endpoints, we examined the many stages in the life cycle of coal, using a framework of environmental externalities, or "hidden costs." Externalities occur when the activity of one agent affects the well-being of another agent outside of any type of market mechanism—these are often not taken into account in decision making and when they are not accounted for, they can distort the decision-making process and reduce the welfare of society.[20] This work strives to derive monetary values for these externalities so that they can be used to inform policy making.

This paper tabulates a wide range of costs associated with the full life cycle of coal, separating those that are quantifiable and monetizable; those that are quantifiable, but difficult to monetize; and those that are qualitative.

A literature review was conducted to consolidate all impacts of coal-generated electricity over its life cycle, monetize and tabulate those that are monetizable, quantify those that are quantifiable, and describe the qualitative impacts. Since there is some uncertainty in the monetization of the damages, low, best, and high estimates are presented. The monetizable impacts found are damages due to climate change; public health damages from NO_x, SO_2, $PM_{2.5}$, and mercury emissions; fatalities of members of the public due to rail accidents during coal transport; the public health burden in Appalachia associated with coal mining; government subsidies; and lost value of abandoned mine lands. All values are presented in 2008 US$. Much of the research we draw upon represented uncertainty by presenting low and/or high estimates in addition to best estimates. Low and high values can indicate both uncertainty in parameters and different assumptions about the parameters that others used to calculate their estimates. Best estimates are not weighted averages, and are derived differently for each category, as explained below.

Climate impacts were monetized using estimates of the social cost of carbon—the valuation of the damages due to emissions of one metric ton of carbon, of \$30/ton of CO_2equivalent (CO_2e),[20] with low and high estimates of \$10/ton and \$100/ton. There is uncertainty around the total cost of climate change and its present value, thus uncertainty concerning the social cost of carbon derived from the total costs. To test for sensitivity to the assumptions about the total costs, low and high estimates of the social cost of carbon were used to produce low and high estimates for climate damage, as was done in the 2009 National Research Council (NRC) report on the "Hidden Costs of Energy."[20] To be consistent with the NRC report, this work uses a low value of \$10/ton CO_2e and a high value of \$100/ton CO_2e.

All public health impacts due to mortality were valued using the value of statistical life (VSL). The value most commonly used by the U.S. Environmental Protection Agency (EPA), and used in this paper, is the central estimate of \$6 million 2000 US$, or \$7.5 million in 2008 US$.[20]

Two values for mortality risk from exposure to air pollutants were found and differed due to different concentration-response functions—increases in mortality risk associated with exposure to air pollutants. The values derived using the lower of the two concentration-response functions is our low estimate, and the higher of the two concentration-response functions is our best and high estimate, for reasons explained below. The impacts on cognitive development and cardiovascular disease due to mercury exposure provided low, best, and high estimates, and these are presented here.

Regarding federal subsidies, two different estimates were found. To provide a conservative best estimate, the lower of the two values represents our low and best estimate, and the higher represents our high estimate. For the remaining costs, one point estimate was found in each instance, representing our low, best, and high estimates.

The monetizable impacts were normalized to per kWh of electricity produced, based on EIA estimates of electricity produced from coal, as was done in the NRC report tabulating externalities due to coal.[2,20] Some values were for all coal mining, not just for the portion emitted due to coal-derived electricity. To correct for this, the derived values were multiplied by the proportion of coal that was used for electrical power, which was approximately 90% in all years analyzed. The additional impacts from nonpower uses of coal, however, are not included in this analysis but do add to the assessment of the complete costs of coal.

To validate the findings, a life cycle assessment of coal-derived electricity was also performed using the Ecoinvent database in SimaPro v 7.1.[25] Health-related impact pathways were monetized using the value of disability-adjusted life-years from ExternE,[26] and the social costs of carbon.[20] Due to data limitations, this method could only be used to validate damages due to a subset of endpoints.

Box 2.

Summary Stats

1. Coal accounted for 25% of global energy consumption in 2005, but generated 41% of the CO_2 emissions that year.
2. In the United States, coal produces just over 50% of the electricity, but generates over 80% of the CO_2 emissions from the utility sector.[2]
3. Coal burning produces one and a half times more CO_2 emissions than does burning oil and twice that from burning natural gas (to produce an equal amount of energy).
4. The energy penalty from CCS (25–40%) would increase the amount of coal mined, transported, processed, and combusted, and the waste generated.[4]
5. Today, 70% of rail traffic in the United States is dedicated to shipping coal.[20] Land and transport would be further stressed with greater dependence on coal.

Life cycle impacts of coal

The health and environmental hazards associated with coal stem from extraction, processing, transportation and combustion of coal; the aerosolized, solid, and liquid waste stream associated with mining, processing, and combustion; and the health, environmental, and economic impacts of climate change (Table 1).

Underground mining and occupational health

The U.S. Mine Safety and Health Administration (MSHA) and the National Institute for Occupational Safety and Health (NIOSH) track occupational injuries and disabilities, chronic illnesses, and mortality in miners in the United States. From 1973 to 2006 the incidence rate of all nonfatal injuries decreased from 1973 to 1987, then increased dramatically in 1988, then decreased from 1988 to 2006.[27] Major accidents still occur. In January 2006, 17 miners died in Appalachian coal mines, including 12 at the Sago mine in West Virginia, and 29 miners died at the Upper Big Branch Mine in West VA on April 5, 2010. Since 1900 over 100,000 have been killed in coal mining accidents in the United States.[14]

In China, underground mining accidents cause 3,800–6,000 deaths annually,[28] though the number of mining-related deaths has decreased by half over the past decade. In 2009, 2,631 coal miners were killed by gas leaks, explosions, or flooded tunnels, according to the Chinese State Administration of Work Safety.[29]

Black lung disease (or pneumoconiosis), leading to chronic obstructive pulmonary disease, is the primary illness in underground coal miners. In the 1990s, over 10,000 former U.S. miners died from coal workers' pneumoconiosis and the prevalence has more than doubled since 1995.[30] Since 1900 coal workers' pneumoconiosis has killed over 200,000 in the United States.[14] These deaths and illnesses are reflected in wages and workers' comp, costs considered internal to the coal industry, but long-term support often depends on state and federal funds.

Again, the use of "coking" coal used in industry is also omitted from this analysis: a study performed in Pittsburgh demonstrated that rates of lung cancer for those working on a coke oven went up two and one-half times, and those working on the top level had the highest (10-fold) risk.[31]

Mountaintop removal

MTR is widespread in eastern Kentucky, West Virginia, and southwestern Virginia. To expose coal seams, mining companies remove forests and fragment rock with explosives. The rubble or "spoil"

then sits precariously along edges and is dumped in the valleys below. MTR has been completed on approximately 500 sites in Kentucky, Virginia, West Virginia, and Tennessee,[32] completely altering some 1.4 million acres, burying 2,000 miles of streams.[33] In Kentucky, alone, there are 293 MTR sites, over 1,400 miles of streams damaged or destroyed, and 2,500 miles of streams polluted.[34–36] Valley fill and other surface mining practices associated with MTR bury headwater streams and contaminate surface and groundwater with carcinogens and heavy metals[16] and are associated with reports of cancer clusters,[37] a finding that requires further study.

The deforestation and landscape changes associated with MTR have impacts on carbon storage and water cycles. Life cycle GHG emissions from coal increase by up to 17% when those from deforestation and land transformation by MTR are included.[38] Fox and Campbell estimated the resulting emissions of GHGs due to land use changes in the Southern Appalachian Forest, which encompasses areas of southern West Virginia, eastern Kentucky, southwestern Virginia, and portions of eastern Tennessee, from a baseline of existing forestland.[38] They estimated that each year, between 6 and 6.9 million tons of CO_2e are emitted due to removal of forest plants and decomposition of forest litter, and possibly significantly more from the mining "spoil" and lost soil carbon.

The fate of soil carbon and the fate of mining spoil, which contains high levels of coal fragments, termed "geogenic organic carbon," are extremely uncertain and the results depend on mining practices at particular sites; but they may represent significant emissions. The Fox and Campbell[38] analysis determined that the worst-case scenario is that all soil carbon is lost and that all carbon in mining spoil is emitted—representing emissions of up to 2.6 million tons CO_2e from soil and 27.5 million tons CO_2e from mining spoil. In this analysis, the 6 million tons CO_2e from forest plants and forest litter represents our low and best estimates for all coal use, and 37 million tons CO_2e (the sum of the high bound of forest plants and litter, geogenic organic carbon, and the forest soil emissions) represents our high, upper bound estimate of emissions for all coal use. In the years Fox and Campell studied, 90.5% of coal was used for electricity, so we attribute 90.5% of these emissions to coal-derived power.[2] To monetize and bound our estimate for damages due to emissions from land disturbance, our point estimate for the cost was calculated using a social cost of carbon of \$30/ton CO_2e and our point estimate for emissions; the high-end estimate was calculated using the high-end estimate of emissions and a social cost of carbon of \$100/ton CO_2e; and the low estimate was calculated using the point estimate for emissions and the \$10/ton low estimate for the social cost of carbon.[20] Our best estimate is therefore \$162.9 million, with a range from \$54.3 million and \$3.35 billion, or 0.008¢/kWh, ranging from 0.003 ¢/kWh to 0.166 ¢/kWh.

The physical vulnerabilities for communities near MTR sites include mudslides and dislodged boulders and trees, and flash floods, especially following heavy rain events. With climate change, heavy rainfall events (2, 4, and 6 inches/day) have increased in the continental United States since 1970, 14%, 20%, and 27% respectively.[39,40]

Blasting to clear mountain ridges adds an additional assault to surrounding communities.[16] The blasts can damage houses, other buildings, and infrastructure, and there are numerous anecdotal reports that the explosions and vibrations are taking a toll on the mental health of those living nearby.

Additional impacts include losses in property values, timber resources, crops (due to water contamination), plus harm to tourism, corrosion of buildings and monuments, dust from mines and explosions, ammonia releases (with formation of ammonium nitrate), and releases of methane.[41]

Methane

In addition to being a heat-trapping gas of high potency, methane adds to the risk of explosions, and fires at mines.[20,42] As of 2005, global atmospheric methane levels were approximately 1,790 parts per billion (ppb), which is an 27 ppb increase over 1998.[43] Methane is emitted during coal mining and it is 25 times more potent than CO_2 during a 100-year timeframe (this is the 100-year global warming potential, a common metric in climate science and policy used to normalize different GHGs to carbon equivalence). When methane decays, it can yield CO_2, an effect that is not fully assessed in this equivalency value.[43]

According to the EIA,[2] 71,100,000 tons CO_2e of methane from coal were emitted in 2007 but

Table 1. The life cycle impact of the U.S. coal industry

	Economic	Human health	Environment	Other
Underground coal mining	1. Federal and state subsidies of coal industry	1. Increased mortality and morbidity in coal communities due to mining pollution	1. Methane emissions from coal leading to climate change	
		2. Threats remaining from abandoned mine lands	2. Remaining damage from abandoned mine lands	
MTR mining	1. Tourism loss	1. Contaminated streams	1. Loss of biodiversity	
	2. Significantly lower property values	2. Direct trauma in surrounding communities	2. Sludge and slurry ponds	
	3. Cost to taxpayers of environmental mitigation and monitoring (both mining and disposal stages)	3. Additional mortality and morbidity in coal communities due to increased levels of air particulates associated with MTR mining (vs. underground mining)	3. Greater levels of air particulates	
	4. Population declines	4. Higher stress levels	4. Loss and contamination of streams	
Coal mining	1. Opportunity costs of bypassing other types of economic development (especially for MTR mining)	1. Workplace fatalities and injuries of coal miners	1. Destruction of local habitat and biodiversity to develop mine site	1. Infrastructure damage due to mudslides following MTR
	2. Federal and state subsidies of coal industry	2. Morbidity and mortality of mine workers resulting from air pollution (e.g., black lung, silicosis)	2. Methane emissions from coal leading to climate change	2. Damage to surrounding infrastructure from subsidence
	3. Economic boom and bust cycle in coal mining communities	3. Increased mortality and morbidity in coal communities due to mining pollution	3. Loss of habitat and streams from valley fill (MTR)	3. Damages to buildings and other infrastructure due to mine blasting
	4. Cost of coal industry litigation	4. Increased morbidity and mortality due to increased air particulates in communities proximate to MTR mining	4. Acid mine drainage	4. Loss of recreation availability in coal mining communities

Continued

Table 1. *Continued*

	Economic	Human health	Environment	Other
	5. Damage to farmland and crops resulting from coal mining pollution	5. Hospitalization costs resulting from increased morbidity in coal communities	5. Incomplete reclamation following mine use	5. Population losses in abandoned coal-mining communities
		6. Local health impacts of heavy metals in coal slurry	6. Water pollution from runoff and waste spills	
	6. Loss of income from small scale forest gathering and farming (e.g., wild ginseng, mushrooms) due to habitat loss	7. Health impacts resulting from coal slurry spills and water contamination	7. Remaining damage from abandoned mine lands	
	7. Loss of tourism income	8. Threats remaining from abandoned mine lands; direct trauma from loose boulders and felled trees	8. Air pollution due to increased particulates from MTR mining	
	8. Lost land required for waste disposal	9. Mental health impacts		
	9. Lower property values for homeowners	10. Dental health impacts reported, possibly from heavy metals		
	10. Decrease in mining jobs in MTR mining areas	11. Fungal growth after flooding		
Coal transportation	1. Wear and tear on aging railroads and tracks	1. Death and injuries from accidents during transport	1. GHG emissions from transport vehicles	1. Damage to rail system from coal transportation
		2. Impacts from emissions during transport	2. Damage to vegetation resulting from air pollution	2. Damage to roadways due to coal trucks
Coal combustion	1. Federal and state subsidies for the coal industry	1. Increased mortality and morbidity due to combustion pollution	1. Climate change due to CO_2 and NO_x derived N_2O emissions	1. Corrosion of buildings and monuments from acid rain
	2. Damage to farmland and crops resulting from coal combustion pollution	2. Hospitalization costs resulting from increased morbidity in coal communities	2. Environmental contamination as a result of heavy metal pollution (mercury, selenium, arsenic)	2. Visibility impairment from NO_x emissions

Continued

Table 1. *Continued*

	Economic	Human health	Environment	Other
		3. Higher frequency of sudden infant death syndrome in areas with high quantities of particulate pollution	3. Impacts of acid rain derived from nitrogen oxides and SO_2	
		4. See Levy *et al*.[21]	4. Environmental impacts of ozone and particulate emissions	
			5. Soil contamination from acid rain	
			6. Destruction of marine life from mercury pollution and acid rain	
			7. Freshwater use in coal powered plants	
Waste disposal		1. Health impacts of heavy metals and other contaminants in coal ash and other waste	1. Impacts on surrounding ecosystems from coal ash and other waste	
		2. Health impacts, trauma and loss of property following coal ash spills	2. Water pollution from runoff and fly ash spills	
Electricity transmission	1. Loss of energy in the combustion and transmission phases		1. Disturbance of ecosystems by utility towers and rights of way	1. Vulnerability of electrical grid to climate change associated disasters

only 92.7% of this coal is going toward electricity. This results in estimated damages of $2.05 billion, or 0.08¢/kWh, with low and high estimates of $684 million and $6.84 billion, or 0.034¢/kWh, and 0.34¢/kWh, using the low and high estimates for the social cost of carbon.[20] Life cycle assessment results, based on 2004 data and emissions from a subset of power plants, indicated 0.037 kg of CO_2e of methane emitted per kWh of electricity produced. With the best estimate for the social cost of carbon, this leads to an estimated cost of $2.2 billion, or 0.11¢/kWh. The differences are due to differences in data, and data from a different years. (See Fig. 1 for summary of external costs per kWh.)

Impoundments

Impoundments are found all along the periphery and at multiple elevations in the areas of MTR sites; adjacent to coal processing plants; and as coal combustion waste ("fly ash") ponds adjacent to coal-fired power plants.[47] Their volume and composition have not been calculated.[48] For Kentucky, the number of known waste and slurry ponds alongside MTR sites and processing plants is 115.[49] These

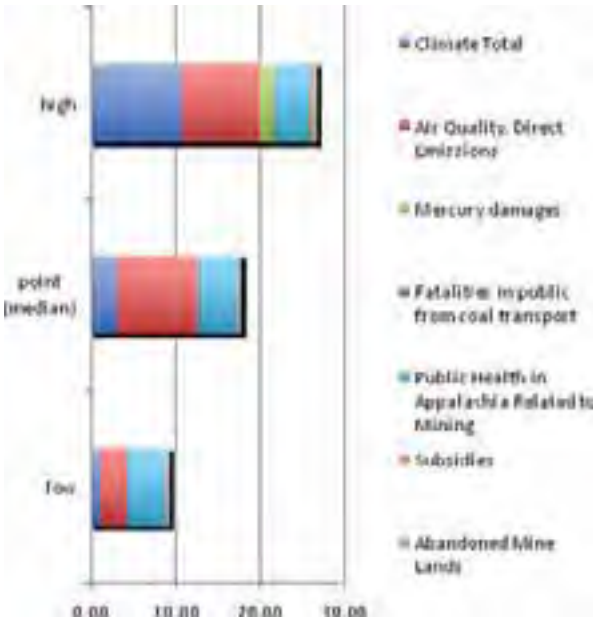

Figure 1. This graph shows the best estimates of the externalities due to coal, along with low and high estimates, normalized to ¢ per kWh of electricity produced. (In color in *Annals* online.)

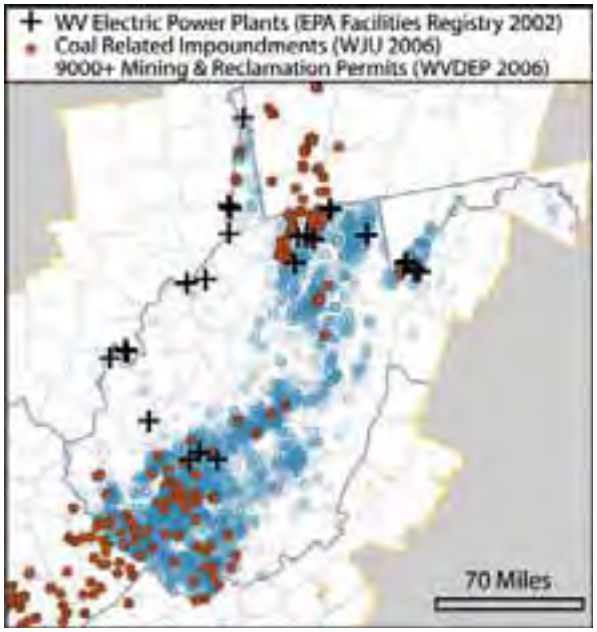

Figure 2. Electric power plants, impoundments (sludge and slurry ponds, CCW, or "fly ash"), and sites slated for reclamation in West Virginia.[44–46] (In color in *Annals* online.) Source: Hope Childers, Wheeling Jesuit University.

sludge, slurry and coal combustion waste (CCW) impoundments are considered by the EPA to be significant contributors to water contamination in the United States. This is especially true for impoundments situated atop previously mined and potentially unstable sites. Land above tunnels dug for long-haul and underground mining are at risk of caving. In the face of heavier precipitation events, unlined containment dams, or those lined with dried slurry are vulnerable to breaching and collapse (Fig. 2).

Processing plants

After coal is mined, it is washed in a mixture of chemicals to reduce impurities that include clay, non-carbonaceous rock, and heavy metals to prepare for use in combustion.[50] Coal slurry is the byproduct of these coal refining plants. In West Virginia, there are currently over 110 billion gallons of coal slurry permitted for 126 impoundments.[49,51] Between 1972 and 2008, there were 53 publicized coal slurry spills in the Appalachian region, one of the largest of which was a 309 million gallon spill that occurred in Martin County, KY in 2000.[48] Of the known chemicals used and generated in processing coal, 19 are known cancer-causing agents, 24 are linked to lung and heart damage, and several remain untested as to their health effects.[52,53]

Coal combustion waste or fly ash

CCW or fly ash—composed of products of combustion and other solid waste—contains toxic chemicals and heavy metals; pollutants known to cause cancer, birth defects, reproductive disorders, neurological damage, learning disabilities, kidney disease, and diabetes.[47,54] A vast majority of the over 1,300 CCW impoundment ponds in the United States are poorly constructed, increasing the risk that waste may leach into groundwater supplies or nearby bodies of water.[55] Under the conditions present in fly ash ponds, contaminants, particularly arsenic, antimony, and selenium (all of which can have serious human health impacts), may readily leach or migrate into the water supplied for household and agricultural use.[56]

According to the EPA, annual production of CCW increased 30% per year between 2000 and 2004, to 130 million tons, and is projected to increase to over 170 million tons by 2015.[57] Based on a series of state estimates, approximately 20% of the total is injected into abandoned coal mines.[58]

In Kentucky, alone, there are 44 fly ash ponds adjacent to the 22 coal-fired plants. Seven of these ash ponds have been characterized as "high hazard"

by the EPA, meaning that if one of these impoundments spilled, it would likely cause significant property damage, injuries, illness, and deaths. Up to 1 in 50 residents in Kentucky, including 1 in 100 children, living near one of the fly ash ponds are at risk of developing cancer as a result of water- and air-borne exposure to waste.[47]

Box 3.

Tennessee Valley Authority Fly Ash Pond Spill

On December 2, 2008 an 84-acre CCW containment area spilled when the dike ruptured at the Tennessee Valley Authority Kingston Fossil Plant CCW impoundment, following heavy rains. Over one billion gallons of fly ash slurry spilled across 300 acres.

Local water contamination

Over the life cycle of coal, chemicals are emitted directly and indirectly into water supplies from mining, processing, and power plant operations. Chemicals in the waste stream include ammonia, sulfur, sulfate, nitrates, nitric acid, tars, oils, fluorides, chlorides, and other acids and metals, including sodium, iron, cyanide, plus additional unlisted chemicals.[16,50]

Spath and colleagues[50] found that these emissions are small in comparison to the air emissions. However, a more recent study performed by Koornneef and colleagues[59] using up-to-date data on emissions and impacts, found that emissions and seepage of toxins and heavy metals into fresh and marine water were significant. Elevated levels of arsenic in drinking water have been found in coal mining areas, along with ground water contamination consistent with coal mining activity in areas near coal mining facilities.[16,17,60,61] In one study of drinking water in four counties in West Virginia, heavy metal concentrations (thallium, selenium, cadmium, beryllium, barium, antimony, lead, and arsenic) exceeded drinking water standards in one-fourth of the households.[48] This mounting evidence indicates that more complete coverage of water sampling is needed throughout coal-field regions.

Carcinogen emissions

Data on emissions of carcinogens due to coal mining and combustion are available in the Ecoinvent database.[25] The eco-indicator impact assessment method was used to estimate health damages in disability-adjusted life years due to these emissions,[25] and were valued using the VSL-year.[26] This amounted to $11 billion per year, or 0.6 ¢/kWh, though these may be significant underestimates of the cancer burden associated with coal.

Of the emissions of carcinogens in the life cycle inventory (inventory of all environmental flows) for coal-derived power, 94% were emitted to water, 6% to air, and 0.03% were to soil, mainly consisting of arsenic and cadmium (note: these do not sum to 100% due to rounding).[25] This number is not included in our total cost accounting to avoid double counting since these emissions may be responsible for health effects observed in mining communities.

Mining and community health

A suite of studies of county-level mortality rates from 1979–2004 by Hendryx found that all-cause mortality rates,[62] lung cancer mortality rates,[60] and mortality from heart, respiratory, and kidney disease[17] were highest in heavy coal mining areas of Appalachia, less so in light coal mining areas, lesser still in noncoal mining areas in Appalachia, and lowest in noncoal mining areas outside of Appalachia. Another study performed by Hendryx and Ahern[18] found that self-reports revealed elevated rates of lung, cardiovascular and kidney diseases, and diabetes and hypertension in coal-mining areas. Yet, another study found that for pregnant women, residing in coal mining areas of West Virginia posed an independent risk for low birth weight (LBW) infants, raising the odds of an LBWs infant by 16% relative to women residing in counties without coal mining.[63] LBW and preterm births are elevated,[64] and children born with extreme LBW fare worse than do children with normal birth weights in almost all neurological assessments;[65] as adults, they have more chronic diseases, including hypertension and diabetes mellitus.[66] Poor birth outcomes are especially elevated in areas with MTR mining as compared with areas with other forms of mining.[67] MTR mining has increased in the areas studied, and is occurring close to population centers.[62]

The estimated excess mortality found in coal mining areas is translated into monetary costs using the VSL approach. For the years 1997–2005, excess age-adjusted mortality rates in coal mining areas of Appalachia compared to national rates

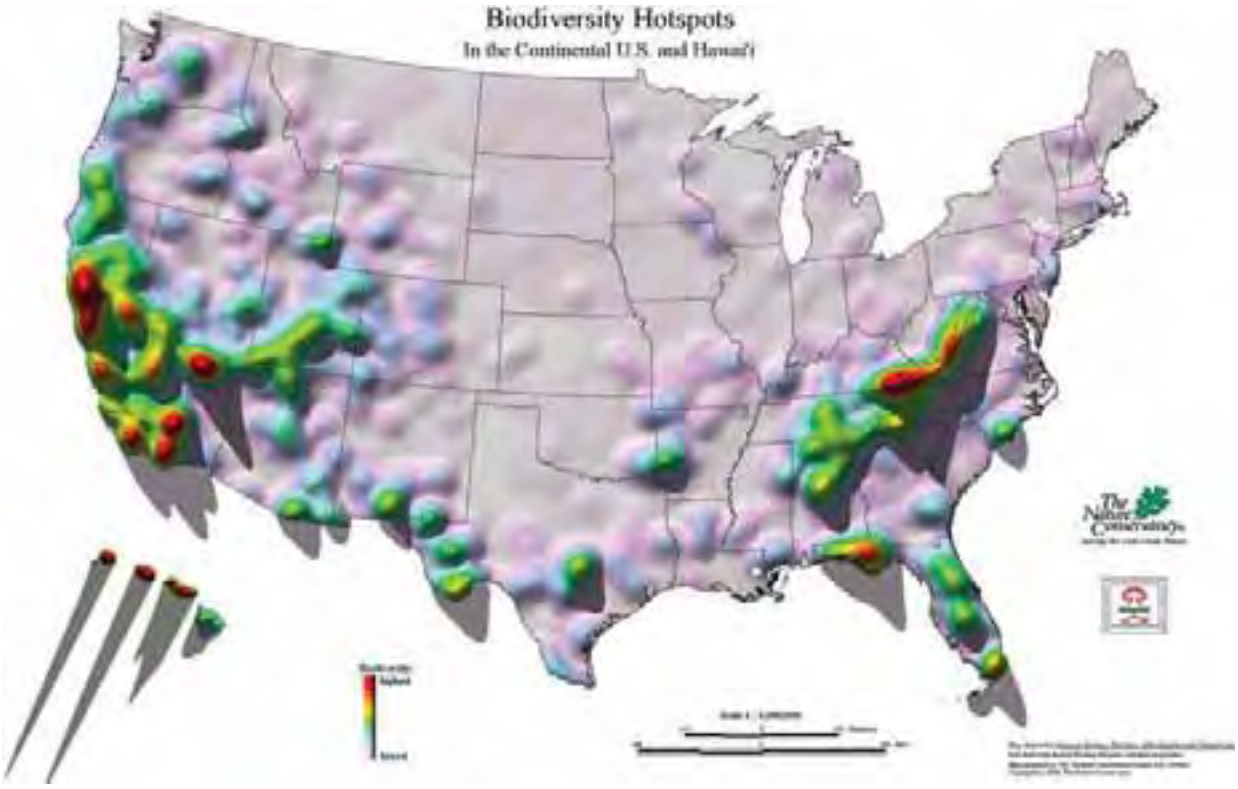

Figure 3. **Areas of highest biological diversity in the continental United States. Source: The Nature Conservancy, Arlington, VA. (In color in *Annals* online.)**

outside Appalachia translates to 10,923 excess deaths every year, with 2,347 excess deaths every year after, adjusting for other soci-oeconomic factors, including smoking rates, obesity, poverty, and access to health care. These socio-economic factors were statistically significantly worse in coal-mining areas.[18,62,68]

Using the VSL of $7.5 million,[20] the unadjusted mortality rate, and the estimate that 91% of coal during these years was used for electricity,[2] this translates to a total cost of $74.6 billion, or 4.36¢/kWh. In contrast, the authors calculated the direct (monetary value of mining industry jobs, including employees and proprietors), indirect (suppliers and others connected to the coal industry), and induced (ripple or multiplier effects throughout the economies) economic benefits of coal mining to Appalachia, and estimated the benefits to be $8.08 billion in 2005 US$.

Ecological impacts

Appalachia is a biologically and geologically rich region, known for its variety and striking beauty. There is loss and degradation of habitat from MTR; impacts on plants and wildlife (species losses and species impacted) from land and water contamination, and acid rain deposition and altered stream conductivity; and the contributions of deforestation and soil disruption to climate change.[16,20]

Globally, the rich biodiversity of Appalachian headwater streams is second only to the tropics.[69] For example, the southern Appalachian mountains harbor the greatest diversity of salamanders globally, with 18% of the known species world-wide (Fig. 3).[69]

Imperiled aquatic ecosystems

Existence of viable aquatic communities in valley fill permit sites was first elucidated in court testimony leading to the "Haden decision."[70] An interagency study of 30 streams in MTR mining-permit areas focused on the upper, unmapped reaches of headwater streams in West Virginia and Kentucky.[71] In performing this study, the researchers identified 71 genera of aquatic insects belonging to 41 families within eight insect orders. The most widely distributed taxa in 175 samples were found in abundance in 30 streams in five areas slated to undergo MTR.

Electrical conductivity (a measure of the concentration of ions) is used as one indicator of stream health.[72] The EPA recommends that stream conductivity not exceed 500 microsiemens per cm (*u*S/cm). In areas with the most intense mining, in which 92% of the watershed had been mined, a recent study revealed levels of 1,100 *u*S/cm.[72]

Meanwhile, even levels below 500 *u*S/cm were shown to significantly affect the abundance and composition of macroinvertebrates, such as mayflies and caddis flies.[73] "Sharp declines" were found in some stream invertebrates where only 1% of the watershed had been mined.[74,75]

Semivoltine aquatic insects (e.g., many stoneflies and dragonflies)—those that require multiple years in the larval stage of development—were encountered in watersheds as small as 10–50 acres. While many of these streams become dry during the late summer months, they continue to harbor permanent resident taxonomic groups capable of withstanding summer dry conditions. Salamanders, the top predatory vertebrates in these fishless headwater streams, depend on permanent streams for their existence.

Mussels are a sensitive indicator species of stream health. Waste from surface mines in Virginia and Tennessee running off into the Clinch and Powell Rivers are overwhelming and killing these filter feeders, and the populations of mussels in these rivers has declined dramatically. Decreases in such filter feeders also affect the quality of drinking water downstream.[76]

In addition, stream dwelling larval stages of aquatic insects are impossible to identify to the species level without trapping adults or rearing larvae to adults.[77] However, no studies of adult stages are conducted for mining-permit applications.

The view that—because there are so many small streams and brooks in the Appalachians—destroying a portion represents a minor threat to biodiversity is contrary to the science. As the planet's second-oldest mountain range, geologically recent processes in Appalachia in the Pleistocene epoch (from 2.5 million to 12,000 years ago) have created conditions for diversification, resulting in one of the U.S. biodiversity "hotspots" (Fig. 3).

Thus, burying an entire 2,000 hectare watershed, including the mainstream and tributaries, is likely to eliminate species of multiple taxa found only in Appalachia.

Researchers have concluded that many unknown species of aquatic insects have likely been buried under valley fills and affected by chemically contaminated waterways. Today's Appalachian coal mining is undeniably resulting in loss of aquatic species, many of which will never be known. Much more study is indicated to appreciate the full spectrum of the ecological effects of MTR mining.[78]

Transport

There are direct hazards from transport of coal. People in mining communities report that road hazards and dust levels are intense. In many cases dust is so thick that it coats the skin, and the walls and furniture in homes.[41] This dust presents an additional burden in terms of respiratory and cardiovascular disease, some of which may have been captured by Hendryx and colleagues.[17–19,60,62,67,68,79]

With 70% of U.S. rail traffic devoted to transporting coal, there are strains on the railroad cars and lines, and (lost) opportunity costs, given the great need for public transport throughout the nation.[20]

The NRC report[20] estimated the number of railroad fatalities by multiplying the proportion of revenue-ton miles (the movement of one ton of revenue-generating commodity over one mile) of commercial freight activity on domestic railroads accounted for by coal, by the number of public fatalities on freight railroads (in 2007); then multiplied by the proportion of transported coal used for electricity generation. The number of coal-related fatalities was multiplied by the VSL to estimate the total costs of fatal accidents in coal transportation. A total of 246 people were killed in rail accidents during coal transportation; 241 of these were members of the public and five of these were occupational fatalities. The deaths to the public add an additional cost of $1.8 billion, or 0.09¢/kWh.

Social and employment impacts

In Appalachia, as levels of mining increase, so do poverty rates and unemployment rates, while educational attainment rates and household income levels decline.[19]

While coal production has been steadily increasing (from 1973 to 2006), the number of employees at the mines increased dramatically from 1973 to 1979, then decreased to levels below 1973 employment levels.[27] Between 1985 and 2005 employment in the Appalachian coal mining industry declined by 56% due to increases in mechanization for MTR and

other surface mining.[19,27] There are 6,300 MTR and surface mining jobs in West Virginia, representing 0.7–0.8% of the state labor force.[2] Coal companies are also employing more people through temporary mining agencies and populations are shifting: between 1995 and 2000 coal-mining West Virginian counties experienced a net loss of 639 people to migration compared with a net migration gain of 422 people in nonmining counties.[19,80]

Combustion

The next stage in the life cycle of coal is combustion to generate energy. Here we focus on coal-fired electricity-generating plants. The by-products of coal combustion include CO_2, methane, particulates and oxides of nitrogen, oxides of sulfur, mercury, and a wide range of carcinogenic chemicals and heavy metals.[20]

Long-range air pollutants and air quality. Data from the U.S. EPA's Emissions & Generation Resource Integrated Database (eGRID)[81] and National Emissions Inventory (NEI)[82] demonstrates that coal power is responsible for much of the U.S. power generation-related emissions of $PM_{2.5}$ (51%), NO_x (35%), and SO_2 (85%). Along with primary emissions of the particulates, SO_2 and NO_x contribute to increases in airborne particle concentrations through secondary transformation processes.[20,21,83]

Studies in New England[84] find that, although populations within a 30-mile radius of coal-fired power plants make up a small contribution to aggregate respiratory illness, on a per capita basis, the impacts on those nearby populations are two to five times greater than those living at a distance. Data in Kentucky suggest similar zones of high impact.

The direct health impacts of SO_2 include respiratory illnesses—wheezing and exacerbation of asthma, shortness of breath, nasal congestion, and pulmonary inflammation—plus heart arrhythmias, LBW, and increased risk of infant death.

The nitrogen-containing emissions (from burning all fossil fuels and from agriculture) cause damages through several pathways. When combined with volatile organic compounds, they can form not only particulates but also ground-level ozone (photochemical smog). Ozone itself is corrosive to the lining of the lungs, and also acts as a local heat-trapping gas.

Epidemiology of air pollution. Estimates of nonfatal health endpoints from coal-related pollutants vary, but are substantial—including 2,800 from lung cancer, 38,200 nonfatal heart attacks and tens of thousands of emergency room visits, hospitalizations, and lost work days.[85] A review[83] of the epidemiology of airborne particles documented that exposure to $PM_{2.5}$ is linked with all-cause premature mortality, cardiovascular and cardiopulmonary mortality, as well as respiratory illnesses, hospitalizations, respiratory and lung function symptoms, and school absences. Those exposed to a higher concentration of $PM_{2.5}$ were at higher risk.[86] Particulates are a cause of lung and heart disease, and premature death,[83] and increase hospitalization costs. Diabetes mellitus enhances the health impacts of particulates[87] and has been implicated in sudden infant death syndrome.[88] Pollution from two older coal-fired power plants in the U.S. Northeast was linked to approximately 70 deaths, tens of thousands of asthma attacks, and hundreds of thousands of episodes of upper respiratory illnesses annually.[89]

A reanalysis of a large U.S. cohort study on the health effects of air pollution, the Harvard Six Cities Study, by Schwartz *et al.*[90] used year-to-year changes in $PM_{2.5}$ concentrations instead of assigning each city a constant $PM_{2.5}$ concentration. To construct one composite estimate for mortality risk from $PM_{2.5}$, the reanalysis also allowed for yearly lags in mortality effects from exposure to $PM_{2.5}$, and revealed that the relative risk of mortality increases by 1.1 per 10 $\mu g/m^3$ increase in $PM_{2.5}$ the year of death, but just 1.025 per 10 $\mu g/m^3$ increase in $PM_{2.5}$ the year before death. This indicates that most of the increase in risk of mortality from $PM_{2.5}$ exposure occurs in the same year as the exposure. The reanalysis also found little evidence for a threshold, meaning that there may be no "safe" levels of $PM_{2.5}$ and that all levels of $PM_{2.5}$ pose a risk to human health.[91]

Thus, prevention strategies should be focused on continuous reduction of $PM_{2.5}$ rather than on peak days, and that air quality improvements will have effect almost immediately upon implementation. The U.S. EPA annual particulate concentration standard is set at 15.0 $\mu g/m^3$, arguing that there is no evidence for harm below this level.[92] The results of the Schwartz *et al.*[90] study directly contradict this line of reasoning.

Risk assessment. The risk assessment performed by the NRC,[20] found aggregate damages of $65 billion, including damages to public health, property, crops, forests, foregone recreation, and visibility due to emissions from coal-fired power plants of $PM_{2.5}$, PM_{10}, SO_2, NO_x, volatile organic compounds, and ozone. The public health damages included mortality cases, bronchitis cases, asthma cases, hospital admissions related to respiratory, cardiac, asthma, coronary obstructive pulmonary disease, and ischemic heart disease problems, and emergency room visits related to asthma. On a plant-by-plant basis after being normalized to electricity produced by each plant, this was 3.2 ¢/kWh. Plant-by-plant estimates of the damages ranged from 1.9 ¢/kWh to 12 ¢/kWh. Plant-to-plant variation was largely due to controls on the plant, characteristics of the coal, and the population downwind of the plant. Emissions of SO_2 were the most damaging of the pollutants affecting air quality, and 99% of this was due to SO_2 in the particle form.[20] The NRC study found that over 90% of the damages due to air quality are from $PM_{2.5}$-related mortality, which implies that these damages included approximately 8,158 excess mortality cases.[20] For the state of Kentucky alone, for each ton of SO_2 removed from the stack, the NRC (2009)[20] calculated a public health savings of $5,800. Removing the close to 500,000 tons emitted in Kentucky would save over $2.85 billion annually. The life cycle analysis found that damages from air quality public health impacts, monetized using methods from ExternE[26] are approximately $70.5 billion, which is roughly in line with this number.

The NRC's estimate is likely an underestimate, since the NRC used the concentration-response curve from Pope and Dockery,[83] which provides a low estimate for increases in mortality risk with increases in $PM_{2.5}$ exposure and is an outlier when compared to other studies examining the $PM_{2.5}$–mortality relationship.[6,87] Had they used the result of the more recent study by Schwartz *et al.*,[90] which was used in a similar study by Levy *et al.*,[21] or the number from Dockery *et al.*,[93] the value they calculated would have been approximately three times higher,[20] therefore implying 24,475 excess deaths in 2005, with a cost of $187.5 billion, or 9.3¢/kWh. As the Schwartz *et al.* study is more recent, uses elaborate statistical techniques to derive the concentration-response function for $PM_{2.5}$ and mortality, and is now widely accepted,[21,94] we use it here to derive our best and high estimate, and the Pope and Dockery,[83] estimate to derive our low. Our best and high estimates for the damages due to air quality detriment impacts are both $187.5 billion, and our low is $65 billion. On a per-kWh basis, this is an average cost of 9.3 ¢/kWh with a low estimate of 3.2 ¢/kWh.

Atmospheric nitrogen deposition. In addition to the impacts to air quality and public health, nitrogen causes ecological harm via eutrophication. Eutrophication, caused by excess nitrogen inputs to coastal river zones, is the greatest source of water quality alteration in the United States and atmospheric deposition is one of the dominant sources of nitrogen inputs.[95] In an analysis by Jaworkski *et al.*,[95] prepared for the EPA, 10 benchmark watersheds in the U.S. Northeast that flowed into the Atlantic coastal zone with good historical data were analyzed in conjunction with emissions data and reconstructed historical emissions. They found that the contribution to riverine nitrogen from nitrogen deposited from the air ranged from 36% to 80%, with a mean of 64%.

The other primary sources of nitrogen are fertilizers from point (e.g., river) discharges and nonpoint (e.g., agricultural land) sources, and other point sources including sewage from cities and farm animals, especially concentrated animal feeding operations.[95] Anthropogenic contributions of nitrogen are equal to the natural sources, doubling this form of fertilization of soils and water bodies.[96]

Harmful algal blooms and dead zones

Ocean and water changes are not usually associated with coal. But nitrogen deposition is a by-product of combustion and the EPA[97] has reached consensus on the link between aquatic eutrophication and harmful algal blooms (HABs), and concluded that nutrient over-fertilization is one of the reasons for their expansion in the United States and other nations. HABs are characterized by discolored water, dead and dying fish, and respiratory irritants in the air, and have impacts including illness and death, beach closures, and fish, bird, and mammal die-offs from exposure to toxins. Illnesses in humans include gastroenteritis, neurological deficits, respiratory illness, and diarrheic, paralytic, and neurotoxic shellfish poisonings.

N_2O from land clearing is a heat-trapping gas[38,42] and adds to the nitrogen deposited in soils and water

bodies. The nitrogen is also a contributor to fresh and sea water acidification.[98–100] Other factors include the loss of wetlands that filter discharges.[98–100]

The economic losses from HABs are estimated to be over $82 million/year in the United States, based on the most prominent episodes.[101,102] The full economic costs of HABs include public health impacts and health care costs, business interruptions of seafood and other allied industries (such as tourism and recreation, unemployment of fin- and shellfish fisherman and their families), and disruptions of international trade.[98–100]

The overfertilization of coastal zones worldwide has also led to over 350 "dead zones" with hypoxia, anoxia, and death of living marine organisms. Commercial and recreational fisheries in the Gulf of Mexico generate $2.8 billion annually[103] and losses from the heavily eutrophied Gulf of Mexico dead zone put the regional economy at risk.

Acid precipitation. In addition to the health impacts of SO_2, sulfates contribute to acid rain, decreased visibility, and have a greenhouse cooling influence.[20]

The long-term Hubbard Brook Ecosystem Study[104] has demonstrated that acid rain (from sulfates and nitrates) has taken a toll on stream and lake life, and soils and forests in the United States, primarily in the Northeast. The leaching of calcium from soils is widespread and, unfortunately, the recovery time is much longer than the time it takes for calcium to become depleted under acidic conditions.[105]

No monetized values of costs were found but a value for the benefits of improvements to the Adirondack State Park from acid rain legislation was produced by Resources for the Future, and found benefits ranging from $336 million to $1.1 billion per year.[106]

Mercury. Coal combustion in the U.S. releases approximately 48 tons of the neurotoxin mercury each year.[54] The most toxic form of mercury is methylmercury, and the primary route of human exposure is through consumption of fin- and shellfish containing bioaccumulated methylmercury.[107] Methylmercury exposure, both dietary and *in utero* through maternal consumption, is associated with neurological effects in infants and children, including delayed achievement of developmental milestones and poor results on neurobehavioral tests—attention, fine motor function, language, visual-spatial abilities, and memory. Seafood consumption has caused 7% of women of childbearing age to exceed the mercury reference dose set by the EPA, and 45 states have issued fish consumption advisories.[107] Emission controls specific to mercury are not available, though 74–95% of emitted mercury is captured by existing emissions control equipment. More advanced technologies are being developed and tested.[107]

Direct costs of mercury emissions from coal-fired power plants causing mental retardation and lost productivity in the form of IQ detriments were estimated by Trasande *et al.*[22,23] to be $361.2 million and $1.625 billion, respectively, or 0.02¢/kWh and 0.1¢/kWh, respectively. Low-end estimates for these values are $43.7 million and $125 million, or 0.003¢/kWh and 0.007¢/kWh; high-end estimates for these values are $3.3 billion and $8.1 billion, or 0.19¢/kWh and 0.48¢/kWh.

There are also epidemiological studies suggesting an association between methylmercury exposure and cardiovascular disease.[108] Rice *et al.*[109] monetized the benefits of a 10% reduction in mercury emissions for both neurological development and cardiovascular health, accounting for uncertainty that the relationship between cardiovascular disease and methylmercury exposure is indeed causal. Applying these results for the cardiovascular benefits of a reduction in methylmercury to the 41% of total U.S. mercury emissions from coal[22,23] indicates costs of $3.5 billion, with low and high estimates of $0.2 billion and $17.9 billion, or 0.2 ¢/kWh, with low and high estimates of 0.014 ¢/kWh and 1.05 ¢/kWh.

Coal's contributions to climate change

The Intergovernmental Panel on Climate Change (IPCC) reported that annual global GHG emissions have—between 1970 and 2004—increased 70% to 49.0 Gt CO_2-e/year.[109] The International Energy Agency's Reference Scenario estimates that worldwide CO_2 emissions will increase by 57% between 2005 and 2030, or 1.8% each year, to 41,905 Mt.[1] In the same time period, CO_2 emissions from coal-generated power are projected to increase 76.6% to 13,884 Mt.[1]

In 2005, coal was responsible for 82% of the U.S.'s GHG emissions from power generation.[110] In addition to direct stack emissions, there are methane

emissions from coal mines, on the order of 3% of the stack emissions.[110] There are also additional GHG emissions from the other uses of coal, approximately 139 Mt CO_2.[1]

Particulate matter (black carbon or soot) is also a heat-trapping agent, absorbing solar radiation, and, even at great distances, decreasing reflectivity (albedo) by settling in snow and ice.[111–113] The contribution of particulates (from coal, diesel, and biomass burning) to climate change has, until recently, been underestimated. Though short-lived, the global warming potential per volume is 500 times that of CO_2.[111]

Climate change

Since the 1950s, the world ocean has accumulated 22 times as much heat as has the atmosphere,[114] and the pattern of warming is unmistakably attributable to the increase in GHGs.[115] Via this ocean repository and melting ice, global warming is changing the climate: causing warming, altered weather patterns, and sea level rise. Climate may change gradually or nonlinearly (in quantum jumps). The release of methane from Arctic seas and the changes in Earth's ice cover (thus albedo), are two potential amplifying feedbacks that could accelerate the rate of Earth's warming.

Just as we have underestimated the rate at which the climate would change, we have underestimated the pace of health and environmental impacts. Already the increases in asthma, heat waves, clusters of illnesses after heavy rain events and intense storms, and in the distribution of infectious diseases are apparent.[116,117] Moreover, the unfolding impacts of climate instability hold yet even more profound impacts for public health, as the changes threaten the natural life-supporting systems upon which we depend.

The EIA[2] estimated that 1.97 billion tons of CO_2 and 9.3 million tons CO_2e of N_2O were emitted directly from coal-fired power plants. Using the social cost of carbon, this resulted in a total cost of $61.7 billion, or 3.06 ¢/kWh. Using the low and high estimates of the social cost of carbon results in cost of $20.56 billion to $205.6 billion, or 1.02 ¢/kWh to 10.2 ¢/kWh.

Black carbon emissions were also calculated using data from the EPA's eGRID database[81] on electricity produced from lignite. The low, mean, and high energy density values for lignite[5] was then used to calculate the amount of lignite consumed. The Cooke *et al.*[118] emissions factor was used to estimate black carbon emissions based on lignite use and the Hansen *et al.*[111] global temperature potential was used to convert these emissions to CO_2e. This resulted in an estimate of 1.5 million tons CO_2e being emitted in 2008, with a value of $45.2 million, or 0.002¢/kWh. Using our low and high estimates for the social cost of carbon and the high and low values for the energy density of lignite produced values of $12.3 million to $161.4 million, or 0.0006 ¢/kWh to 0.008¢/kWh.

One measure of the costs of climate change is the rising costs of extreme weather events, though these are also a function of and real estate and insurance values. Overall, the costs of weather-related disasters rose 10-fold from the 1980s to the 1990s (from an average of $4 bn/year to $40 bn/year) and jumped again in the past decade, reaching $225 bn in 2005.[119] Worldwide, Munich Re—a company that insures insurers—reports that, in 2008, without Katrina-level disasters, weather-related "catastrophic losses" to the global economy were the third-highest in recorded history, topping $200 billion, including $45 billion in the United States.[120]

The total costs of climate change damages from coal-derived power, including black carbon, CO_2 and N_2O emissions from combustion, land disturbance in MTR, and methane leakage from mines, is $63.9 billion dollars, or 3.15 ¢/kWh, with low and high estimates of $21.3 billion to $215.9 billion, or 1.06 ¢/kWh to 10.71 ¢/kWh. A broad examination of the costs of climate change[121] projects global economic losses to between 5 and 20% of global gross domestic product ($1.75–$7 trillion in 2005 US$); the higher figure based on the potential collapse of ecosystems, such as coral reefs and widespread forest and crop losses. With coal contributing at least one-third of the heat-trapping chemicals, these projections offer a sobering perspective on the evolving costs of coal; costs that can be projected to rise (linearly or nonlinearly) over time.

Carbon capture and storage

Burning coal with CO_2 CCS in terrestrial, ocean, and deep ocean sediments are proposed methods of deriving "clean coal." But—in addition to the control technique not altering the upstream life cycle costs—significant obstacles lie in the way, including the costs of construction of suitable plants

Table 2. MIT cost estimates for some representative CCS systems.[5]

		Subcritical PC		Supercritical PC		Ultra-supercritical PC		SC PC-Oxy	IGCC	
		No capture	Capture	No capture	Capture	No capture	Capture	Capture	No capture	Capture
CCS performance	Coal feed (kg/hr)	208,000	284,000	184,894	242,950	164,000	209,000	232,628	185,376	228,115
	CO_2 emitted (kg/hr)	466,000	63,600	414,903	54,518	369,000	46,800	52,202	415,983	51,198
	CO_2 captured at 90%, (kg/h)	0	573.000	0	490662	0	422000	469817	0	460782
	CO_2 emitted (g/kWh)	931	127	830	109	738	94	104	832	102
CCS costs	$/kWh	1,280	2,230	1,330	2,140	1,360	2,090	1,900	1,430	1,890
	Total $, assuming 500 MW plant	$640,000,000	$1,115,000,000	$665,000,000	$1,070,000,000	$680,000,000	$1,045,000,000	$950,000,000	$715,000,000	$945,000,000
	Inv. Charce ¢/kWh @ 15.1%	2.6	4.52	2.7	4.34	2.76	4.24	3.85	2.9	3.83
	Fuel ¢/kWh @ $1.50/MMBtu	1.49	2.04	1.33	1.75	1.18	1.5	1.67	1.33	1.64
	O&M ¢/kWh	0.75	1.6	0.75	1.6	0.75	1.6	1.45	0.9	1.05
	COE ¢/kWh	4.84	8.16	4.78	7.69	4.69	7.34	8.98	5.13	6.52
	Cost of CO_2 avoided vs. same technology w/o capture ($/ton)		41.3		40.4		41.1	30.3		19.3
	Cost of CO_2 avoided vs. supercritical technology w/o capture ($/ton)		48.2		40.4		34.8	30.3		24
	Energy penalty		1,365,384,615		1,313,996,128		1,274,390,244			1,230,553,038

and underground storage facilities, and the "energy penalty" requiring that coal consumption per unit of energy produced by the power plant increase by 25–40% depending on the technologies used.[4,42]

Retrofitting old plants—the largest source of CO_2 in the United States—may exact an even larger energy penalty. The energy penalty means that more coal is needed to produce the same quantity of electricity, necessitating more mining, processing, and transporting of coal and resulting in a larger waste stream to produce the same amount of electricity. Coal-fired plants would still require locally polluting diesel trucks to deliver the coal, and generate CCW ponds that can contaminate ground water. Given current siting patterns, such impacts often fall disproportionately on economically disadvantaged communities. The energy penalty combined with other increased costs of operating a CCS plant would nearly double the cost of generating electricity from that plant, depending on the technology used (see Table 2).[5]

The U.S. Department of Energy estimates that an underground volume of 30,000 km^2 will be needed per year to reduce the CO_2 emissions from coal by 20% by 2050 (the total land mass of the continental U.S. (48 states) is 9,158,960 km^2).[122]

The safety and ensurability of scaling up the storage of the billion tons of CO_2 generated each year into the foreseeable future are unknown. Extrapolating from localized experiments, injecting fractions of the volumes that will have to be stored to make a significant difference in emissions, is fraught with numerous assumptions. Bringing CCS to scale raises additional risks, in terms of pressures underground. In addition to this, according to the U.S. Government Accountability Office (2008) there are regulatory, legal and liability uncertainties, and there is "significant cost of retrofitting existing plants that are single largest source of CO_2 emissions in the United States" (p. 7).[123]

Health and environmental risks of CCS

The Special IPCC Report on Carbon Dioxide Capture and Storage[42] lists the following concerns for CCS in underground terrestrial sites:

1. Storing compressed and liquefied CO_2 underground can acidify saline aquifers (akin to ocean acidification) and leach heavy metals, such as arsenic and lead, into ground water.[42]
2. Acidification of ground water increases fluid-rock interactions that enhance calcite dissolution and solubility, and can lead to fractures in

limestone ($CaCO_3$) and subsequent releases of CO_2 in high concentrations.[124]

3. Increased pressures may cause leaks and releases from previously drilled (often unmapped) pathways.
4. Increased pressures could destabilize underground faults and lead to earthquakes.
5. Large leaks and releases of concentrated CO_2 are toxic to plants and animals.[42]
   a. The 2006 Mammoth Mountain, CA release left dead stands of trees.[124]
6. Microbial communities may be altered, with release of other gases.[42]

The figures in Table 2 represent costs for new construction. Costs for retrofits (where CCS is installed on an active plant) and rebuilds (where CCS is installed on an active plant and the combustion technology is upgraded) are highly uncertain because they are extremely dependent on site conditions and precisely what technology the coal plant is upgraded to.[5] It does appear that complete rebuilds are more economically attractive than retrofits, and that "carbon-capture ready" plants are not economically desirable to build.[5]

Subsidies

In Kentucky, coal brings in an estimated $528 million in state revenues, but is responsible for $643 million in state expenditures. The net impact, therefore, is a loss of $115 million to the state of Kentucky.[126] These figures do not include costs of health care, lost productivity, water treatment for siltation and water infrastructure, limited development potential due to poor air quality, and social expenditures associated with declines in employment and related economic hardships of coal-field communities.[126]

The U.S. Federal Government provides subsides for electricity and mining activities, and these have been tallied by both the EIA and the Environmental Law Institute.[2,127,128] The EIA estimate is $3.17 billion of subsidies in 2007, or 0.16¢/kWh, and the Environmental Law Institute estimate is $5.37 billion for 2007, or 0.27¢/kWh.

Abandoned mine lands

Abandoned mine lands (AML) are those lands and waters negatively impacted by surface coal mining and left inadequately reclaimed or abandoned prior to August 3, 1977.[129] There are over 1,700 old abandoned mines in Pennsylvania, alone.[14] In some—like that in Centralia, PA—fires burn for decades, emitting carbon monoxide, and other fumes. The ground above others can open, and several people die each year falling into them. Still others flood and lead to contaminated ground water. Previous coal mining communities lie in the shadow of these disturbed areas. Officials in Pennsylvania estimate that it will take $15 billion over six decades to clean Pennsylvania's abandoned mines.

Figure 4. **Current high-priority abandoned mine land reclamation sites from Alabama to Pennsylvania.[129] (In color in *Annals* online.) Source: Hope Childers, Wheeling Jesuit University.**

Since the passage of the Surface Mining Control and Reclamation Act of 1977, active mining operations have been required to pay fees into the Abandoned Mine Reclamation Fund that are then used to finance reclamation of these AMLs.[129] Despite the more than $7.4 billion that has been collected as of September 30, 2005, there is a growing backlog of unfunded projects.[51] Data on the number and monetary value of unfunded AML projects remaining at the end of 2007 for the nation were collected directly from the Abandoned Mine Land Inventory System[129] and amounted to $8.8 billion 2008 US$, or 0.44¢/kWh (Fig. 4).

Results

The tabulation of the externalities in total and converted to 2008 US$ is given in Table 3 and normalized to cents per kWh of coal-generated electricity

Table 3. The complete costs of coal as reviewed in this report in 2008 US$.

	Monetized estimates from literature (2008 US$)			Monetized life cycle assessment results (2008 US$)	
	Low	Best	High	IPCC 2007, U.S. Hard Coal	U.S. Hard Coal Eco-indicator
Land disturbance	$54,311,510	$162,934,529	$3,349,209,766		
Methane emissions from mines	$684,084,928	$2,052,254,783	$6,840,849,276	$2,188,192, 405	
Carcinogens (mostly to water from waste)					$11,775,544, 263
Public health burden of communities in Appalachia	$74,612,823,575	$74,612,823,575	$74,612,823,575		
Fatalities in the public due to coal transport	$1,807,500,000	$1,807,500,000	$1,807,500,000		
Emissions of air pollutants from combustion	$65,094,911,734	$187,473,345,794	$187,473,345,794		$71,011,655, 364
Lost productivity from mercury emissions	$125,000,000	$1,625,000,000	$8,125,000,000		
Excess mental retardation cases from mercury emissions	$43,750,000	$361,250,000	$3,250,000,000		
Excess cardiovascular disease from mercury emissions	$246,000,000	$3,536,250,000	$17,937,500,000		
Climate damages from combustion emissions of CO_2 and N_2O	$20,559,709,242	$61,679,127,726	$205,597,092,419.52	$70,442,466, 509	
Climate damages from combustion emissions of black carbon	$12,346,127	$45,186,823	$161,381,512.28	$3,739,876, 478	
Environmental Law Institute estimate 2007			$5,373, 963,368		
EIA 2007	$3,177,964,157	$3,177, 964,157			
AMLs	$8,775,282,692	$8,775, 282,692	$8,775, 282,692		
Climate total	$21,310,451,806	$63,939,503,861	$215,948,532,974		
Total	$175,193,683,964	$345,308,920,080	$523,303,948,403		

A 2010 Clean Air Task Force[56] (CATF) report, with Abt Associates consulting, lists 13,000 premature deaths due to air pollution from all electricity generation in 2010, a decrease in their estimates from previous years. They attribute the drop to 105 scrubbers installed since 2005, the year in which we based our calculations. We were pleased to see improvements reported in air quality and health outcomes. There is, however, considerable uncertainty regarding the actual numbers. Using the epidemiology from the "Six Cities Study" implies up to 34,000 premature deaths in 2010. Thus, our figures are mid-range while those of the CATF represent the most conservative of estimates.

in Table 4. Our best estimate for the externalities related to coal is $345.3 billion (range: $175.2 bn to $523.3 bn). On a per-kWh basis this is 17.84¢/kWh, ranging from 9.42 ¢/kWh to 26.89 ¢/kWh.

Limitations of this analysis

While we have based this analysis on the best available data that are used by a wide range of organizations, this review is limited by the omission of many environmental, community, mental health, and economic impacts that are not easily quantifiable. Another limitation is the placing of numbers on impacts that are difficult to quantify or monetize, including the VSL, a crude estimate of the benefits of reducing the number of deaths used by economists, and the social cost of carbon, based on the evolving impacts of climate change. We have included ranges, reflecting the numerous sets of data and studies in this field (all of which have their own

Table 4. Total costs of coal normalized to kWh of electricity produced.

	Monetized estimates from literature in ¢/kWh of electricity (2008 US$)			Monetized life cycle assessment results in ¢/kWh of electricity (2008 US$)	
	Low	Best	High	IPCC 2007, U.S. Hard Coal	U.S. Hard Coal Eco-indicator
Land disturbance	0.00	0.01	0.17		
Methane emissions from mines	0.03	0.08	0.34	0.11	
Carcinogens (mostly to water from waste)					0.60
Public health burden of communities in Appalachia	4.36	4.36	4.36		
Fatalities in the public due to coal transport	0.09	0.09	0.09		
Emissions of air pollutants from combustion	3.23	9.31	9.31		3.59
Lost productivity from mercury emissions	0.01	0.10	0.48		
Excess mental retardation cases from mercury emissions	0.00	0.02	0.19		
Excess cardiovascular disease from mercury emissions	0.01	0.21	1.05		
Climate damage from combustion emissions of CO_2 and N_2O	1.02	3.06	10.20	3.56	
Climate damages from combustion emissions of black carbon	0.00	0.00	0.01	0.19	
Environmental Law Institute estimate 2007			0.27		
EIA 2007	0.16	0.16			
AMLs	0.44	0.44	0.44		
Climate total	1.06	3.15	10.7	3.75	1.54
Total	9.36	17.84	26.89		

uncertainties), varying assumptions in data sets and studies, and uncertainties about future impacts and the costs to society.

Some of the issues raised apply only to the region discussed. Decreased tourism in Appalachia, for example, affects regional economies; but may not affect the overall economy of the United States, as tourists may choose other destinations.

Studies in Australian coal mining communities illustrate the cycle of economic boom during construction and operation, the economic and worker decoupling from the fortunes of the mines; then the eventual closing.[130] Such communities experience high levels of depression and poverty, and increases in assaults (particularly sexual assaults), motor vehicle accidents, and crimes against

property, until the culture shifts to allow for development of secondary industries. Additional evidence documents that mining-dependent economies tend to be weak economies,[131] and weak economic conditions in turn are powerful predictors of social and health disadvantages.[130,132]

Some values are also difficult to interpret, given the multiple baselines against which they must be compared. In assessing the "marginal" costs of environmental damages, we have assumed the diverse, pristine, hardwood forest that still constitutes the majority of the beautiful rich and rolling hills that make up the Appalachian Mountain range.

Ecological and health economic analyses are also affected by the discount rate used in such evaluations. Discount rates are of great value in assessing the worth of commodities that deteriorate over time. But they are of questionable value in assessing ecological, life-supporting systems that have value if they are sustained. Ecological economists might consider employing a negative discount rate—or an accrual rate—in assessing the true impacts of environmental degradation and the value of sustainability.

Finally, the costs reported here do not include a wide range of opportunity costs, including lost opportunities to construct wind farms and solar power plants, begin manufacture of wind turbines and solar technologies, develop technologies for the smart grid and transmission, and for economic and business development unrelated to the energy sector.

Conclusions

The electricity derived from coal is an integral part of our daily lives. However, coal carries a heavy burden. The yearly and cumulative costs stemming from the aerosolized, solid, and water pollutants associated with the mining, processing, transport, and combustion of coal affect individuals, families, communities, ecological integrity, and the global climate. The economic implications go far beyond the prices we pay for electricity.

Our comprehensive review finds that the best estimate for the total economically quantifiable costs, based on a conservative weighting of many of the study findings, amount to some $345.3 billion, adding close to 17.8¢/kWh of electricity generated from coal. The low estimate is $175 billion, or over 9¢/kWh, while the true monetizable costs could be as much as the upper bounds of $523.3 billion, adding close to 26.89¢/kWh. These and the more difficult to quantify externalities are borne by the general public.

Still these figures do not represent the full societal and environmental burden of coal. In quantifying the damages, we have omitted the impacts of toxic chemicals and heavy metals on ecological systems and diverse plants and animals; some ill-health endpoints (morbidity) aside from mortality related to air pollutants released through coal combustion that are still not captured; the direct risks and hazards posed by sludge, slurry, and CCW impoundments; the full contributions of nitrogen deposition to eutrophication of fresh and coastal sea water; the prolonged impacts of acid rain and acid mine drainage; many of the long-term impacts on the physical and mental health of those living in coal-field regions and nearby MTR sites; some of the health impacts and climate forcing due to increased tropospheric ozone formation; and the full assessment of impacts due to an increasingly unstable climate.

The true ecological and health costs of coal are thus far greater than the numbers suggest. Accounting for the many external costs over the life cycle for coal-derived electricity conservatively doubles to triples the price of coal per kWh of electricity generated.

Our analysis also suggests that the proposed measure to address one of the emissions—CO_2, via CCS—is costly and carries numerous health and environmental risks, which would be multiplied if CCS were deployed on a wide scale. The combination of new technologies and the "energy penalty" will, conservatively, almost double the costs to operate the utility plants. In addition, questions about the reserves of economically recoverable coal in the United States carry implications for future investments into coal-related infrastructure.

Public policies, including the Clean Air Act and New Source Performance Review, are in place to help control these externalities; however, the actual impacts and damages remain substantial. These costs must be accounted for in formulating public policies and for guiding private sector practices, including project financing and insurance underwriting of coal-fired plants with and without CCS.

Recommendations

1. Comprehensive comparative analyses of life cycle costs of all electricity generation

technologies and practices are needed to guide the development of future energy policies.
2. Begin phasing out coal and phasing in cleanly powered smart grids, using place-appropriate alternative energy sources.
3. A healthy energy future can include electric vehicles, plugged into cleanly powered smart grids; and healthy cities initiatives, including green buildings, roof-top gardens, public transport, and smart growth.
4. Alternative industrial and farming policies are needed for coal-field regions, to support the manufacture and installation of solar, wind, small-scale hydro, and smart grid technologies. Rural electric co-ops can help in meeting consumer demands.
5. We must end MTR mining, reclaim all MTR sites and abandoned mine lands, and ensure that local water sources are safe for consumption.
6. Funds are needed for clean enterprises, reclamation, and water treatment.
7. Fund-generating methods include:
   a. maintaining revenues from the workers' compensation coal tax;
   b. increasing coal severance tax rates;
   c. increasing fees on coal haul trucks and trains;
   d. reforming the structure of credits and taxes to remove misaligned incentives;
   e. reforming federal and state subsidies to incentivize clean technology infrastructure.
8. To transform our energy infrastructure, we must realign federal and state rules, regulations, and rewards to stimulate manufacturing of and markets for clean and efficient energy systems. Such a transformation would be beneficial for our health, for the environment, for sustained economic health, and would contribute to stabilizing the global climate.

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Conflicts of interest

The authors declare no conflicts of interest.

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Wind Turbine Sound and Health Effects
An Expert Panel Review

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Acronyms and Abbreviations

μPa	microPascal
ACOEM	American College of Occupational and Environmental Medicine
ANSI	American National Standards Institute
AWEA	American Wind Energy Association
ASHA	American Speech-Language-Hearing Association
CanWEA	Canadian Wind Energy Association
dB	decibel
dBA	decibel (on an A-weighted scale)
DNL	day-night-level
DSM-IV-TR	*Diagnostic and Statistical Manual of Mental Disorders,* Fourth Edition
EPA	U.S. Environmental Protection Agency
FDA	Food and Drug Administration
FFT	Fast Fourier Transform
GI	gastrointestinal
HPA	Health Protection Agency
Hz	Hertz
IARC	International Agency for Research on Cancer
ICD-10	International Statistical Classification of Diseases and Related Health Problems, 10th Revision
IEC	International Engineering Consortium
ISO	International Organization for Standardization
Km	kilometer
kW	kilowatt
L_{eq}	equivalent level
LPALF	large pressure amplitude and low frequency
m/s	meters per second
m/s^2	meters per second squared
NIESH	National Institute of Environmental Health Sciences
NIHL	noise-induced hearing loss
NIOSH	National Institute for Occupational Safety and Health
N/m^2	Newtons per square meter
NRC	National Research Council
NTP	National Toxicology Program
ONAC	Office of Noise Abatement and Control
OSHA	Occupational Safety and Health Administration
Pa	Pascal
UK	United Kingdom
VAD	vibroacoustic disease
VVVD	vibratory vestibular disturbance
VEMP	vestibular evoked myogenic potential response
WHO	World Health Organization

Executive Summary

People have been harnessing the power of the wind for more than 5,000 years. Initially used widely for farm irrigation and millworks, today's modern wind turbines produce electricity in more than 70 countries. As of the end of 2008, there were approximately 120,800 megawatts of wind energy capacity installed around the world (Global Wind Energy Council, 2009).

Wind energy enjoys considerable public support, but it also has its detractors, who have publicized their concerns that the sounds emitted from wind turbines cause adverse health consequences.

In response to those concerns, the American and Canadian Wind Energy Associations (AWEA and CanWEA) established a scientific advisory panel in early 2009 to conduct a review of current literature available on the issue of perceived health effects of wind turbines. This multidisciplinary panel is comprised of medical doctors, audiologists, and acoustical professionals from the United States, Canada, Denmark, and the United Kingdom. The objective of the panel was to provide an authoritative reference document for legislators, regulators, and anyone who wants to make sense of the conflicting information about wind turbine sound.

The panel undertook extensive review, analysis, and discussion of the large body of peer-reviewed literature on sound and health effects in general, and on sound produced by wind turbines. Each panel member contributed a unique expertise in audiology, acoustics, otolaryngology, occupational/ environmental medicine, or public health. With a diversity of perspectives represented, the panel assessed the plausible biological effects of exposure to wind turbine sound.

Following review, analysis, and discussion of current knowledge, the panel reached consensus on the following conclusions:

- There is no evidence that the audible or sub-audible sounds emitted by wind turbines have any direct adverse physiological effects.
- The ground-borne vibrations from wind turbines are too weak to be detected by, or to affect, humans.
- The sounds emitted by wind turbines are not unique. There is no reason to believe, based on the levels and frequencies of the sounds and the panel's experience with sound exposures in occupational settings, that the sounds from wind turbines could plausibly have direct adverse health consequences.

SECTION 1

Introduction

The mission of the American Wind Energy Association (AWEA) is to promote the growth of wind power through advocacy, communication, and education. Similarly, the mission of the Canadian Wind Energy Association (CanWEA) is to promote the responsible and sustainable growth of wind power in Canada. Both organizations wish to take a proactive role in ensuring that wind energy projects are good neighbors to the communities that have embraced wind energy.

Together AWEA and CanWEA proposed to a number of independent groups that they examine the scientific validity of recent reports on the adverse health effects of wind turbine proximity. Such reports have raised public concern about wind turbine exposure. In the absence of declared commitment to such an effort from independent groups, the wind industry decided to be proactive and address the issue itself. In 2009, AWEA and CanWEA commissioned this report. They asked the authors to examine published scientific literature on possible adverse health effects resulting from exposure to wind turbines.

The objective of this report is to address health concerns associated with sounds from industrial-scale wind turbines. Inevitably, a report funded by an industry association will be subject to charges of bias and conflicts of interest. AWEA and CanWEA have minimized bias and conflicts of interest to the greatest possible extent through selection of a distinguished panel of independent experts in acoustics, audiology, medicine, and public health. This report is the result of their efforts.

1.1 Expert Panelists

The experts listed below were asked to investigate and analyze existing literature and publish their findings in this report; their current positions and/or qualifications for inclusion are also provided.

- W. David Colby, M.D.: Chatham-Kent Medical Officer of Health (Acting); Associate Professor, Schulich School of Medicine & Dentistry, University of Western Ontario
- Robert Dobie, M.D.: Clinical Professor, University of Texas, San Antonio; Clinical Professor, University of California, Davis
- Geoff Leventhall, Ph.D.: Consultant in Noise Vibration and Acoustics, UK
- David M. Lipscomb, Ph.D.: President, Correct Service, Inc.
- Robert J. McCunney, M.D.: Research Scientist, Massachusetts Institute of Technology Department of Biological Engineering; Staff Physician, Massachusetts General Hospital Pulmonary Division; Harvard Medical School
- Michael T. Seilo, Ph.D.: Professor of Audiology, Western Washington University

- Bo Søndergaard, M.Sc. (Physics**):** Senior Consultant, Danish Electronics Light and Acoustics (DELTA)

Mark Bastasch, an acoustical engineer with the consulting firm of CH2M HILL, acted as technical advisor to the panel.

1.2 Report Terminology

Certain terms are used frequently throughout this report. Table 1-1 defines these terms. An understanding of the distinction between "sound" and "noise" may be particularly useful to the reader.

TABLE 1-1
Definitions of Acoustical Terms

Term	Definitions
Sound	Describes wave-like variations in air pressure that occur at frequencies that can stimulate receptors in the inner ear and, if sufficiently powerful, be appreciated at a conscious level.
Noise	Implies the presence of sound but also implies a response to sound: noise is often defined as unwanted sound.
Ambient noise level	The composite of noise from all sources near and far. The normal or existing level of environmental noise at a given location.
Decibel (dB)	A unit describing the amplitude of sound, equal to 20 times the logarithm to the base 10 of the ratio of the measured pressure to the reference pressure, which is 20 micropascals (μPa).
A-weighted sound pressure level (dBA)	The sound pressure level in decibels as measured on a sound level meter using the A-weighted filter network. The A-weighted filter de-emphasizes the very low and very high frequency components of the sound in a manner similar to the frequency response of the human ear and correlates well with subjective reactions to noise.
Hertz (Hz)	A unit of measurement of frequency; the number of cycles per second of a periodic waveform.
Infrasound	According to the International Electrotechnical Commission's (IEC's) IEC 1994, infrasound is: Acoustic oscillations whose frequency is below the low-frequency limit of audible sound (about 16 Hz). However this definition is incomplete as infrasound at high enough levels is audible at frequencies below 16 Hz. (IEC (1994): 60050-801:1994 International Electrotechnical Vocabulary - Chapter 801: Acoustics and electroacoustics).
Low-frequency sound	Sound in the frequency range that overlaps the higher infrasound frequencies and the lower audible frequencies, and is typically considered as 10 Hz to 200 Hz, but is not closely defined.

Source: HPA, 2009.

SECTION 2

Methodology

Three steps form the basis for this report: formation of an expert panel, review of literature directly related to wind turbines, and review of potential environmental exposures.

2.1 Formation of Expert Panel

The American and Canadian wind energy associations, AWEA and CanWEA, assembled a distinguished panel of independent experts to address concerns that the sounds emitted from wind turbines cause adverse health consequences.

The objective of the panel was to provide an authoritative reference document for the use of legislators, regulators, and people simply wanting to make sense of the conflicting information about wind turbine sound.

The panel represented expertise in audiology, acoustics, otolaryngology, occupational/ environmental medicine, and public health. A series of conference calls were held among panel members to discuss literature and key health concerns that have been raised about wind turbines. The calls were followed by the development of a draft that was reviewed by other panel members. Throughout the follow-up period, literature was critically addressed.

2.2 Review of Literature Directly Related to Wind Turbines

The panel conducted a search of Pub Med under the heading "Wind Turbines and Health Effects" to research and address peer-reviewed literature. In addition, the panel conducted a search on "vibroacoustic disease." The reference section identifies the peer and non-peer reviewed sources that were consulted by the panel.

2.3 Review of Potential Environmental Exposures

The panel conducted a review of potential environmental exposures associated with wind turbine operations, with a focus on low frequency sound, infrasound, and vibration.

SECTION 3

Overview and Discussion

This section summarizes the results of the review and analysis conducted by the expert panel and responds to a number of key questions:

- How do wind turbine operations affect human auditory response?
- How do we determine the loudness and frequency of sound and its effects on the human ear?
- How do wind turbines produce sound?
- How is sound measured and tested?
- What is vibration?
- **W**hat type of exposure to wind turbines is more likely to be perceived by humans (low frequency sound, infrasound or vibration)?
- Can sounds in the low frequency range, most notably the infrasonic range, adversely affect human health? Even when such levels are below the average person's ability to hear them?
- How does the human vestibular system respond to sound?
- What are the potential adverse effects and health implications of sound exposure?
- What does scientific literature say about wind turbines, low frequency sound, and infrasound?

3.1 Wind Turbine Operation and Human Auditory Response to Sound

3.1.1 Overview

The normal operation of a wind turbine produces sound and vibration, arousing concern about potential health implications. This section addresses the fundamental principles associated with sound and vibration, sound measurement, and potential adverse health implications. Sound from a wind turbine arises from its mechanical operation and the turning of the blades.

3.1.2 The Human Ear and Sound

The human ear is capable of perceiving a wide range of sounds, from the high-pitched sounds of a bird song to the low-pitched sound of a bass guitar. Sounds are perceived based on their loudness (i.e., volume or sound pressure level) or pitch (i.e., tonal or frequency content). The standard unit of measure for sound pressure levels is the decibel (dB). The standard unit used to describe the tonal or frequency content is the Hertz (Hz), measured in cycles per second)—Appendix A provides more information on the fundamentals of sound. Customarily, the young, non-pathological ear can perceive sounds ranging from 20 Hz to 20,000 Hz. Appendix B provides more information on the human ear.

Frequencies below 20 Hz are commonly called "infrasound," although the boundary between infrasound and low frequency sound is not rigid. Infrasound, at certain frequencies and at high levels, can be audible to some people. Low frequency sound is customarily referred to as that between 10 Hz and 200 Hz, but any definition is arbitrary to some degree. Low frequency sound is the subject of concern to some with respect to potential health implications.

TABLE 3-1
TYPICAL SOUND PRESSURE LEVELS MEASURED IN THE ENVIRONMENT AND INDUSTRY

Noise Source At a Given Distance	A-Weighted Sound Level in Decibels	Qualitative Description
Carrier deck jet operation	140	
	130	Pain threshold
Jet takeoff (200 feet)	120	
Auto horn (3 feet)	110	Maximum vocal effort
Jet takeoff (1000 feet) Shout (0.5 feet)	100	
N.Y. subway station Heavy truck (50 feet)	90	Very annoying Hearing damage (8-hour, continuous exposure)
Pneumatic drill (50 feet)	80	Annoying
Freight train (50 feet) Freeway traffic (50 feet)	70 to 80	
	70	Intrusive (Telephone use difficult)
Air conditioning unit (20 feet)	60	
Light auto traffic (50 feet)	50	Quiet
Living room Bedroom	40	
Library Soft whisper (5 feet)	30	Very quiet
Broadcasting/Recording studio	20	
	10	Just audible

Adapted from Table E, "Assessing and Mitigating Noise Impacts", NY DEC, February 2001.

Table 3-1 shows sound pressure levels associated with common activities. Typically, environmental and occupational sound pressure levels are measured in decibels on an A-weighted scale (dBA). The A-weighted scale de-emphasizes the very low and very high frequency components of the sound in a manner similar to the frequency response of the human ear. For comparison, the sound from a wind turbine at distances between 1,000 and 2,000 feet is generally within 40 to 50 dBA.

Section 3.2 discusses the effects of exposure to wind turbine sound. Section 3.3 describes the potential adverse effects of sound exposure as well as the health implications.

3.1.3 Sound Produced by Wind Turbines

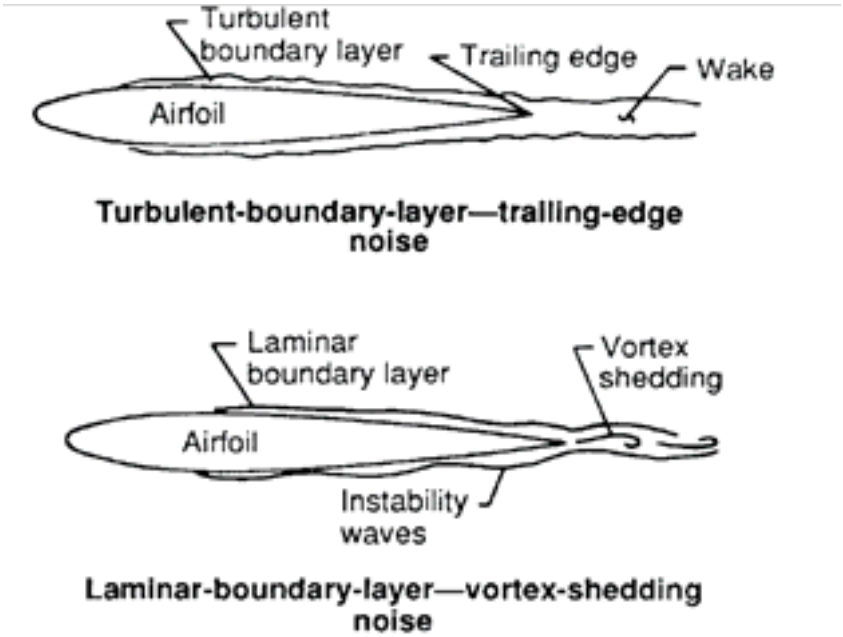
Wind turbine sound originates from either a mechanical or aerodynamic generation mechanism. Mechanical sound originates from the gearbox and control mechanisms. Standard noise control techniques typically are used to reduce mechanical sound. Mechanical noise is not typically the dominant source of noise from modern wind turbines (except for an occasional gear tone).

The aerodynamic noise is present at all frequencies, from the infrasound range over low frequency sound to the normal audible range and is the dominant source. The aerodynamic noise is generated by several mechanisms as is described below. The aerodynamic noise tends to be modulated in the mid frequency range, approximately 500 to 1,000 Hz.

Aerodynamic sound is produced by the rotation of the turbine blades through the air. A turbine blade shape is that of an airfoil. An airfoil is simply a structure with a shape that produces a lift force when air passes over it. Originally developed for aircraft, airfoil shapes have been adapted to provide the turning force for wind turbines by employing a shape which causes the air to travel more rapidly over the top of the airfoil than below it. The designs optimize efficiency by minimizing turbulence, which produces drag and noise. An aerodynamically efficient blade is a quiet one.

The aerodynamic sound from wind turbines is caused by the interaction of the turbine blade with the turbulence produced both adjacent to it (turbulent boundary layer) and in its near wake (see Figure 3-1) (Brooks et al., 1989). Turbulence depends on how fast the blade is moving through the air. A 100-meter-diameter blade, rotating once every three seconds, has a tip velocity of just over 100 meters per second. However, the speed reduces at positions closer to the centre of rotation (the wind turbine hub). The main determinants of the turbulence are the speed of the blade and the shape and dimensions of its cross-section.

FIGURE 3-1
Sound Produced by Wind Turbine Flow



The following conclusions have been derived from the flow conditions shown in Figure 3-1 (Brooks et al., 1989):

- At high velocities for a given blade, turbulent boundary layers develop over much of the airfoil. Sound is produced when the turbulent boundary layer passes over the trailing edge.
- At lower velocities, mainly laminar boundary layers develop, leading to vortex shedding at the trailing edge.

Other factors in the production of aerodynamic sound include the following:

- When the angle of attack is not zero—in other words, the blade is tilted into the wind—flow separation can occur on the suction side near to the trailing edge, producing sound.
- At high angles of attack, large-scale separation may occur in a stall condition, leading to radiation of low frequency sound.
- A blunt trailing edge leads to vortex shedding and additional sound.
- The tip vortex contains highly turbulent flow.

Each of the above factors may contribute to wind turbine sound production. Measurements of the location of the sound source in wind turbines indicate that the dominant sound is produced along the blade—nearer to the tip end than to the hub. Reduction of turbulence sound can be facilitated through airfoil shape and by good maintenance. For example, surface irregularities resulting from damage or to accretion of additional material, may increase the sound.

Aerodynamic sound has been shown to be generated at higher levels during the downward motion of the blade (i.e., the three o'clock position). This results in a rise in level of approximately once per second for a typical three-bladed turbine. This periodic rise in level is also referred to as amplitude modulation, and as described above for a typical wind turbine, the modulation frequency is 1 Hz (once per second). In other words, the sound level rises and falls about once per second. The origin of this amplitude modulation is not fully understood. It was previously assumed that the modulation was caused when the blade went past the tower (given the tower disturbed the airflow), but it is now thought to be related to the difference in wind speed between the top and bottom of the rotation of a blade and directivity of the aerodynamic noise (Oerlemans and Schepers, 2009).

In other words, the result of aerodynamic modulation is a perceivable fluctuation in the sound level of approximately once per second. The frequency content of this fluctuating sound is typically between 500 Hz and 1,000 Hz, but can occur at higher and lower frequencies. That is, the sound pressure levels between approximately 500 and 1,000 Hz will rise and fall approximately once per second. It should be noted, however, that the magnitude of the amplitude modulation that is observed when standing beneath a tower does not always occur at greater separation distances. A study in the United Kingdom (UK) also showed that only four out of about 130 wind farms had a problem with aerodynamic modulation and three of these have been solved (Moorhouse et al., 2007).

In addition to the sound levels generated by the turbines, environmental factors affect the levels received at more distant locations. For example, warm air near the ground causes the turbine sound to curve upwards, away from the ground, which results in reduced sound levels, while warm air in a temperature inversion may cause the sound to curve down to the earth resulting in increased sound levels. Wind may also cause the sound level to be greater downwind of the turbine—that is, if the wind is blowing from the source towards a receiver—or lower, if the wind is blowing from the receiver to the source. Most modeling techniques, when properly implemented, account for moderate inversions and downwind conditions. Attenuation (reduction) of sound can also be influenced by barriers, ground surface conditions, shrubbery and trees, among other things.

Predictions of the sound level at varying distances from the turbine are based on turbine sound power levels. These turbine sound power levels are determined through standardized measurement methods.

3.1.4 Sound Measurement and Audiometric Testing

A sound level meter is a standard tool used in the measurement of sound pressure levels. As described in Section 3.1.2, the standard unit of sound pressure level (i.e., volume) is dB and the standard unit used to describe the pitch or frequency is Hz (cycles per second). A sound level meter may use the A-weighting filter to adjust certain frequency ranges (those that humans detect poorly), resulting in a reading in dBA (decibels, A-weighted). Appendix C provides more information on the measurement of sound. The pitch or frequencies (sometimes referred to as sound level spectrum**)** can be quantified using a sound level meter that includes a frequency analyzer. Octave band, one-third octave band, and narrow band (such as Fast Fourier Transform, or FFT) are three common types of frequency analyzers.

Consider, for example, a routine audiometric test (hearing test) in which a person sits in a booth and wears headphones, through which sounds are transmitted to evaluate hearing. Outside the booth, a technician turns a dial which yields certain frequencies (for example, 125 Hz, a low-pitched sound, or 4,000 Hz, a high-pitched sound) and then the technician raises the volume of each frequency until the person recognizes the sound of each tone. This is a standard approach used to measure thresholds for many reasons, including noise-induced hearing loss (NIHL). As the technician raises the volume of the designated frequency, the sound level (in dB) is noted. People who need more than 25 dB at more than one frequency to hear the sound (ie loudness of the tone) are considered to have an abnormal test.

The effects of prolonged, high-level sound exposure on hearing have been determined through audiometric tests of workers in certain occupations. The studies have been published in major medical journals and subjected to the peer review process (see, for example, McCunney and Meyer, 2007). Studies of workers have also served as the scientific basis for regulations on noise in industry that are overseen by the Occupational Safety and Health Administration (OSHA). Workers in noise-intensive industries have been evaluated for NIHL and certain industries are known to be associated with high noise levels, such as aviation, construction, and areas of manufacturing such as canning. Multiyear worker studies suggest that prolonged exposure to high noise levels can adversely affect hearing. The levels considered sufficiently high to cause hearing loss are considerably higher than one could experience in the vicinity of wind turbines. For example, prolonged, unprotected high exposure to noise at levels greater than 90 dBA is a risk for hearing loss in occupational settings such that OSHA established this level for hearing protection. Sound levels from wind turbines do not approach these levels (50 dBA at a distance of 1,500 feet would be a conservative estimate for today's turbines). Although the issue of NIHL has rarely been raised in opposition to wind farms, it is important to note that the risk of NIHL is directly dependent on the intensity (sound level) and duration of noise exposure and therefore it is reasonable to conclude that there is no risk of NIHL from wind turbine sound. Such a conclusion is based on studies of workers exposed to noise and among whom risk of NIHL is not apparent at levels less than 75 dBA.

3.2 Sound Exposure from Wind Turbine Operation

This section addresses the questions of (1) whether sounds in the low frequency range, most notably the infrasonic range, adversely affect human health, and whether they do so even when such levels are below the average person's ability to hear them; (2) what we are referring to when we talk about vibration; and (3) how the human vestibular system responds to sound and disturbance.

3.2.1 Infrasound and Low-Frequency Sound

Infrasound and low frequency sound are addressed in some detail to offer perspective on publicized hypotheses that sound from a wind turbine may damage health even if the noise levels are below those associated with noise-induced hearing loss in industry. For example, it has been proposed that sounds that contain low frequency noise, most notably within the infrasonic level, can adversely affect health even when the levels are below the average person's ability to detect or hear them (Alves-Pereira and Branco, 2007b).

Comprehensive reviews of infrasound and its sources and measurement have been published (Berglund and Lindvall, 1995; Leventhall et al., 2003). Table 3-2 shows the sound pressure level, in decibels, of the corresponding frequency of infrasound and low frequency sound necessary for the sound to be heard by the average person (Leventhall et al., 2003).

TABLE 3-2
Hearing Thresholds in the Infrasonic and Low Frequency Range

re uenc	4	8	10	16	20	25	40	50	80	100	125	160	200
Sound pressure level d	107	100	97	88	79	69	51	44	32	27	22	18	14

N
Average hearing thresholds (for young healthy people) in the infrasound (4 to 20 Hz) and low frequency region (10 to 200 Hz).

Source: Leventhall et al., 2003

As Table 3-2 indicates, at low frequencies, a much higher level sound is necessary for a sound to be heard in comparison to higher frequencies. For example, at 10 Hz, the sound must be at 97 dB to be audible. If this level occurred at the mid to high frequencies, which the ear detects effectively, it would be roughly equivalent to standing without hearing protection directly next to a power saw. Decibel for decibel, the low frequencies are much more difficult to detect than the high frequencies, as shown in the hearing threshold levels of Table 3-2.

Table 3-2 also shows that even sounds as low as 4 Hz can be heard if the levels are high enough (107 dB). However, levels from wind turbines at 4 Hz are more likely to be around 70 dB or lower, and therefore inaudible. Studies conducted to assess wind turbine noise have shown that wind turbine sound at typical distances does not exceed the hearing threshold and will not be audible below about 50 Hz (Hayes 2006b; Kamperman and James, 2008). The hearing threshold level at 50 Hz is 44 dB, as shown in Table 3-2. Recent work on evaluating a large number of noise sources between 10 Hz and 160 Hz suggests that wind turbine noise heard indoors at typical separation distances is modest on the scale of low frequency sound sources (Pedersen, 2008). The low levels of infrasound and low frequency sound from wind turbine operations have been confirmed by others (Jakobsen, 2004; van den Berg, 2004).

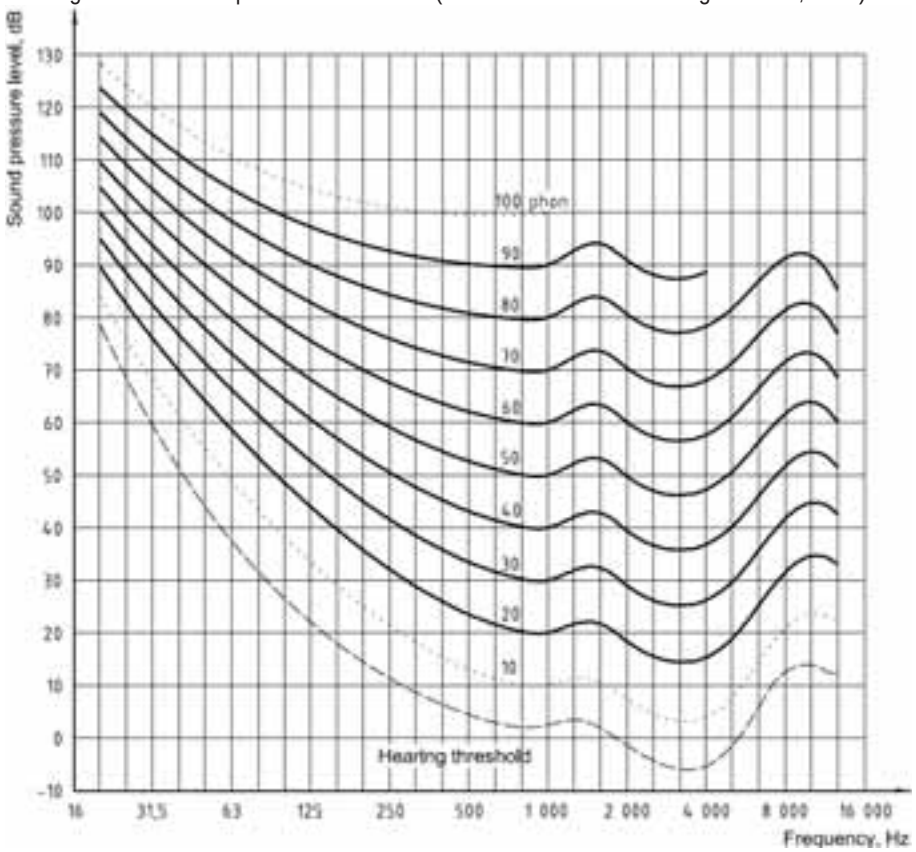
The low frequency sound associated with wind turbines has attracted attention recently since the A-weighting scale that is used for occupational and environmental regulatory compliance does not work well with sounds that have prominently low frequency components. Most environmental low frequency sound problems are caused by discrete tones (pitch or tones that are significantly higher in level (volume) than the neighboring frequencies); from, for example, an engine or compressor, not by continuous broadband sound. The high frequency sounds are assessed by the A-weighted measurement and, given their shorter wavelengths, are controlled more readily. Low frequency sounds may be irritating to some people and, in fact, some low frequency sound complaints prove impossible to resolve (Leventhall et al., 2003). This observation leads to a perception that there is something special, sinister, and harmful about low frequency sound. To the contrary, most external sound when heard indoors is biased towards low frequencies due to the efficient building attenuation of higher frequencies. One may recognize this when noise

from a neighbor's stereo is heard within their home—the bass notes are more pronounced than the higher frequency sounds. Any unwanted sound, whether high frequency or low frequency, can be irritating and stressful to some people.

Differences in how a low frequency sound and high frequency sound are perceived are well documented. Figure 3-2 shows that lower-frequency sounds typically need to be at a high sound pressure level (dB) to be heard. Figure 3-2 also demonstrates that as the frequency lowers, the audible range is compressed leading to a more rapid rise in loudness as the level changes in the lower frequencies. At 1,000 Hz, the whole range covers about 100 dB change in sound pressure level, while at 20 Hz the same range of loudness covers about 50 dB (note the contours displayed in Figure 3-2 are in terms of phons, a measure of equal loudness; for additional explanation on phons, the reader is referred to http://www.sfu.ca/sonic-studio/handbook/Phon.html [Truax, 1999]). As the annoyance of a given sound increases as loudness increases, there is also a more rapid growth of annoyance at low frequencies. However, there is no evidence for direct physiological effects from either infrasound or low frequency sound at the levels generated from wind turbines, indoors or outside. Effects may result from the sounds being audible, but these are similar to the effects from other audible sounds.

Low frequency sound and infrasound are further addressed in Section 3.3, Potential Adverse Effects of Exposure to Sound.

FIGURE 3-2
Hearing Contours for Equal Loudness Level (International Standards Organization, 2003)



3.2.2 Vibration

Vibration, assumed to result from inaudible low frequency sounds, has been postulated to have a potential adverse effect on health. This section defines vibration, describes how it is measured, and cites studies that have addressed the risk of vibration on health.

Vibration refers to the way in which energy travels through solid material, whether steel, concrete in a bridge, the earth, the wall of a house or the human body. Vibration is distinguished from sound, which is energy flowing through gases (like air) or liquids (like water).

As higher frequency vibrations attenuate rapidly, it is low frequencies which are of potential concern to human health. When vibration is detected through the feet or through the seat, the focus of interest is the vibration of the surface with which one is in contact—for example, when travelling in a vehicle.

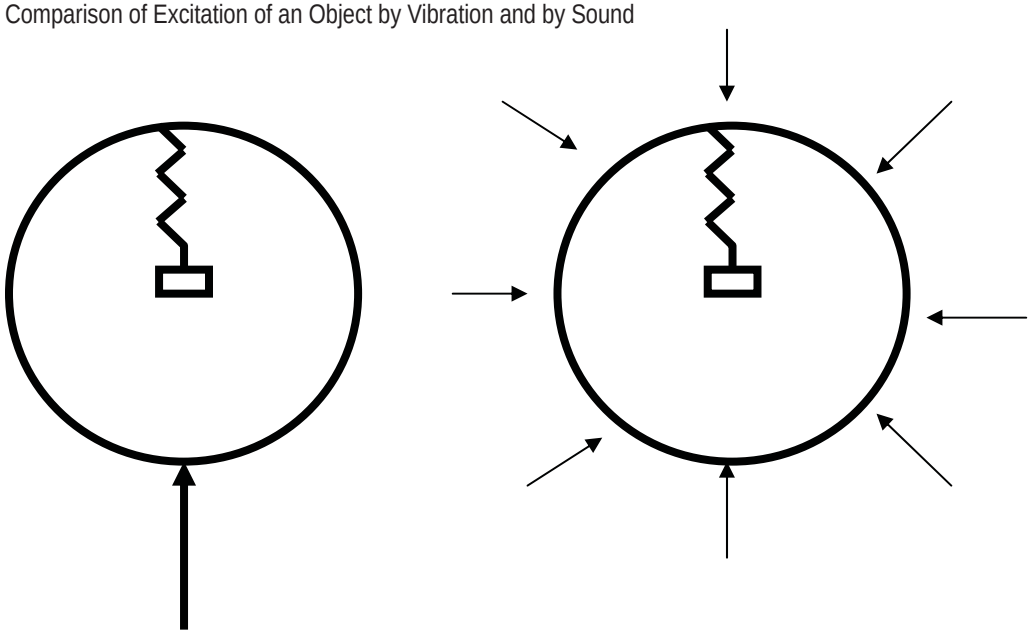
Vibration is often measured by the acceleration of the surface in meters per second, squared (m/s^2), although other related units are used. Vibration can also be expressed in decibels, where the reference excitation level used in buildings is often $10^{-5} m/s^2$ and the vibration level is $20\log (A/10^{-5})$ dB, where A is the acceleration level in m/s^2.

The threshold of perception of vibration by humans is approximately 0.01 m/s^2. If a frequency of excitation (vibration) corresponds with a resonant frequency of a system, then

excitation at the resonant frequency is greater than at other frequencies. However, excitation by sound is not the same as excitation by mechanical excitation applied at, say, the feet.

Figure 3-3 shows an object excited by point mechanical vibration and by sound. The object contains a resiliently suspended system. For example, if the object was the body, the suspended system might be the viscera (internal organs of the body). The left hand of the figure can be interpreted as the body vibrated by input to the feet. The vibration of the viscera will be maximum at the resonant frequency[1] of the suspended system, which, for viscera, is about 4 Hz. When excitation is by long wavelength low frequency sound waves, as shown at the right of the figure, not only is the force acting on the body much smaller than for vibration input, but, as the wavelength is much greater than the dimensions of the body, it is acting around the body in a compressive manner so that there is no resultant force on the suspended system and it does not vibrate or resonate.

FIGURE 3-3
Comparison of Excitation of an Object by Vibration and by Sound



Unfortunately, this lack of effect has not been addressed by those who have suggested the mechanical vibration response of the body instead of the acoustic response as a potential health consequence. This oversight has led to inaccurate conclusions. For example, Dr. Nina Pierpont bases one of her key hypotheses for the cause of "wind turbine syndrome" on such an egregious error (Pierpont, 2009, pre-publication draft). Although not a recognized medical diagnosis, "wind turbine syndrome" has been raised as a concern for proposed projects—refer to Section 4.3 for more information.

Vibration of the body by sound at one of its resonant frequencies occurs only at very high sound levels and is not a factor in the perception of wind turbine noise. As will be discussed

[1] A common example of resonance is pushing a child on a swing in which energy is given to the swing to maximize its oscillation.

below, the sound levels associated with wind turbines do not affect the vestibular or other balance systems.

3.2.3 Vestibular System

The vestibular system of the body plays a major role in maintaining a person's sense of balance and the stabilization of visual images. The vestibular system responds to pressure changes (sound pressure, i.e., decibels) at various frequencies. At high levels of exposure to low frequency sound, nausea and changes in respiration and blood pressure may occur. Studies have shown, however, that for these effects to occur, considerably high noise levels (greater than 140 dB, similar in sound level of a jet aircraft heard 80 feet away) are necessary (Berglund et al., 1996).

Head vibration resulting from low frequency sound has been suggested as a possible cause of a variety of symptoms that some hypothesize as being associated with wind turbines. In order to properly assess this hypothesis, this section addresses the human vestibular system. The "vestibular system" comprises the sense organs in the vestibular labyrinth, in which there are five tiny sensory organs: three semicircular canals that detect head rotation and two chalk-crystal-studded organs called otoliths (literally "ear-stones") that detect tilt and linear motion of the head. All five organs contain hair cells, like those in the cochlea, that convert motion into nerve impulses traveling to the brain in the vestibular nerve.

These organs evolved millions of years before the middle ear. Fish, for example, have no middle ear or cochlea but have a vestibular labyrinth nearly identical to ours (Baloh and Honrubia, 1979). The vestibular organs are specialized for stimulation by head position and movement, not by airborne sound. Each vestibular organ is firmly attached to the skull, to enable them to respond to the slightest head movement. In contrast, the hair cells in the cochlea are not directly attached to the skull; they do not normally respond to head movement, but to movements of the inner ear fluids.

The otolith organs help fish hear low frequency sounds; even in primates, these organs will respond to head vibration (i.e., bone-conducted sound) at frequencies up to 500 Hz (Fernandez and Goldberg, 1976). These vibratory responses of the vestibular system can be elicited by *airborne* sounds, however, only when they are at a much higher level than normal hearing thresholds[2] (and much higher than levels associated with wind turbine exposure). Thus, they do not help us hear but appear to be vestiges of our evolutionary past.

The vestibular nerve sends information about head position and movement to centers in the brain that also receive input from the eyes and from stretch receptors in the neck, trunk, and

[2] Young et al. (1977) found that neurons coming from the vestibular labyrinth of monkeys responded to head vibration at frequencies of 200-400 Hz, and at levels as low as 70 to 80 dB below gravitational force. However, these neurons could not respond to airborne sound at the same frequencies until levels exceeded 76 dB sound pressure level (SPL), which is at least 40 dB higher than the normal threshold of human hearing in this frequency range. Human eye movements respond to 100 Hz head vibration at levels 15 dB below audible levels (Todd et al., 2008a). This does not mean that the vestibular labyrinth is more sensitive than the cochlea to airborne sound, because the impedance-matching function of the middle ear allows the cochlea to respond to sounds that are 50-60 dB less intense than those necessary to cause detectable head vibration. Indeed, the same authors (Todd et al., 2008b) found that for airborne sound, responses from the cochlea could always be elicited by sounds that were below the threshold for vestibular responses. Similarly, Welgampola et al. (2003) found that thresholds for vestibular evoked myogenic potential response (VEMP) were higher than hearing thresholds and stated: "the difference between hearing thresholds and VEMP thresholds is much greater for air conducted sounds than for bone vibration." In other words, the vestigial vestibular response to sound is relatively sensitive to bone conduction, which involves vibration of the whole head, and much less sensitive to air conduction.

legs (these stretch receptors tell which muscles are contracted and which joints are flexed, and provide the "proprioceptive" sense of the body's position and orientation in space). The brain integrates vestibular, visual, and proprioceptive inputs into a comprehensive analysis of the position and movement of the head and body, essential for the sense of balance, avoidance of falls, and keeping the eyes focused on relevant targets, even during movement.

Perception of the body's position in space may also rely in part on input from receptors in abdominal organs (which can shift back and forth as the body tilts) and from pressure receptors in large blood vessels (blood pools in the legs when standing, then shifts back to the trunk when lying down). These "somatic graviceptors" (Mittelstaedt, 1996) could be activated by whole-body movement and possibly by structure-borne vibration, or by the blast of a powerful near explosion, but, as described in Section 4.3.2, it is unlikely that intra-abdominal and intra-thoracic organs and blood vessels could detect airborne sound like that created by wind turbines.

Trauma, toxins, age-related degeneration, and various ear diseases can cause disorders of the vestibular labyrinth. A labyrinth not functioning properly can cause a person to feel unsteady or even to fall. Since the semicircular canals of the ear normally detect head rotation (such as shaking the head to indicate "no"), one of the consequences of a dysfunctional canal is that a person may feel a "spinning" sensation. This reaction is described as vertigo, from the Latin word to turn. In normal conversation, words like vertigo and dizziness can be used in ambiguous ways and thus make careful interpretation of potential health claims problematic. "Dizzy," for example, may mean true vertigo or unsteadiness, both of which may be symptoms of inner ear disease. A person who describes being "dizzy" may actually be experiencing light-headedness, a fainting sensation, blurred vision, disorientation, or almost any other difficult-to-describe sensation in the head. The word "dizziness" can represent different sensations to each person, with a variety of causes. This can make the proper interpretation of research studies in which dizziness is evaluated a challenge to interpret.

Proper diagnostic testing to evaluate dizziness can reduce errors in misclassifying disease. The vestibular labyrinth, for example, can be tested for postural stability. Information from the semicircular canals is fed to the eye muscles to allow us to keep our eyes focused on a target; when the head moves; this "vestibulo-ocular reflex" is easily tested and can be impaired in vestibular disorders (Baloh and Honrubia, 1979).

3.3 Potential Adverse Effects of Exposure to Sound

Adverse effects of sound are directly dependent on the sound level; higher frequency sounds present a greater risk of an adverse effect than lower levels (see Table 3-2). Speech interference, hearing loss, and task interference occur at high sound levels. Softer sounds may be annoying or cause sleep disturbance in some people. At normal separation distances, wind turbines do not produce sound at levels that cause speech interference, but some people may find these sounds to be annoying.

3.3.1 Speech Interference

It is common knowledge that conversation can be difficult in a noisy restaurant; the louder the background noise, the louder we talk and the harder it is to communicate. Average

levels of casual conversation at 1 meter (arm's length) are typically 50 to 60 dBA. People raise their voices—slightly and unconsciously at first—when ambient levels exceed 50 to 55 dBA, in order to keep speech levels slightly above background noise levels. Communication at arm's length requires conscious extra effort when levels exceed about 75 dBA. Above ambient levels of 80 to 85 dBA, people need to shout or get closer to converse (Pearsons et al., 1977; Webster, 1978). Levels below 45 dBA can be considered irrelevant with respect to speech interference.

3.3.2 Noise-Induced Hearing Loss

Very brief and intense sounds (above 130 dBA, such as in explosions) can cause instant cochlear damage and permanent hearing loss, but most occupational NIHL results from prolonged exposure to high noise levels between 90 and 105 dBA (McCunney and Meyer 2007). Regulatory (OSHA, 1983) and advisory (NIOSH, 1998) authorities in the U.S. concur that risk of NIHL begins at about 85 dBA, for an 8-hour day, over a 40-year career. Levels below 75 dBA do not pose a risk of NIHL. Thus, the sound levels associated with wind turbine operations would not cause NIHL because they are not high enough.

3.3.3 Task Interference

Suter (1991) reviewed the effects of noise on performance and behavior. Simple tasks may be unaffected even at levels well above 100 dBA, while more complex tasks can be disrupted by intermittent noise as low as 75 dBA. Speech sounds are usually more disruptive than nonspeech sounds. Levels below 70 dBA do not result in task interference.

3.3.4 Annoyance

Annoyance as a possible "effect" of wind turbine operations is discussed in detail in later sections of this report (Sections 3.4 and 4.1). In summary, annoyance is a subjective response that varies among people to many types of sounds. It is important to note that although annoyance may be a frustrating experience for people, it is not considered an adverse health effect or disease of any kind. Certain everyday sounds, such as a dripping faucet—barely audible—can be annoying. Annoyance cannot be predicted easily with a sound level meter. Noise from airports, road traffic, and other sources (including wind turbines) may annoy some people, and, as described in Section 4.1, the louder the noise, the more people may become annoyed.

3.3.5 Sleep Disturbance

The U.S. Environmental Protection Agency (EPA) document titled *Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety* (1974) recommends that indoor day-night-level (DNL) not exceed 45 dBA. DNL is a 24-hour average that gives 10 dB extra weight to sounds occurring between 10p.m. and 7 a.m., on the assumption that during these sleep hours, levels above 35 dBA indoors may be disruptive.

3.3.6 Other Adverse Health Effects of Sound

At extremely high sound levels, such as those associated with explosions, the resulting sound pressure can injure any air-containing organ: not only the middle ear (eardrum

perforations are common) but also the lungs and intestines (Sasser et al., 2006). At the other extreme, any sound that is chronically annoying, including very soft sounds, may, for some people, create chronic stress, which can in turn lead to other health problems. On the other hand, many people become accustomed to regular exposure to noise or other potential stressors, and are no longer annoyed. The hypothesis that chronic noise exposure might lead to chronic health problems such as hypertension and heart disease has been the subject of hundreds of contradictory studies of highly variable quality, which will not be reviewed in this document. Other authors have reviewed this literature, and some of their conclusions are quoted below:

> "It appears not likely that noise in industry can be a direct cause of general health problems…, except that the noise can create conditions of psychological stress…which can in turn cause physiological stress reactions…" (Kryter, 1980)

> "Epidemiological evidence on noise exposure, blood pressure, and ischemic heart disease is still limited." (Babisch, 2004), and "contradictory' (Babisch, 1998), but "there is some evidence…of an increased risk in subjects who live in noisy areas with outdoor noise levels of greater than 65 - 70 dBA." (Babisch, 2000)

> "The present state of the art does not permit any definite conclusion to be drawn about the risk of hypertension." (van Dijk, Ettema, and Zielhuis, 1987)

> "At this point, the relationship between noise induced hearing loss and hypertension must be considered as possible but lacking sufficient evidence to draw causal associations." (McCunney and Meyer, 2007)

3.3.7 Potential Health Effects of Vibration Exposure

People may experience vibration when some part of the body is in direct contact with a vibrating object. One example would be holding a chainsaw or pneumatic hammer in the hands. Another would be sitting in a bus, truck, or on heavy equipment such as a bulldozer. Chronic use of vibrating tools can cause "hand-arm vibration syndrome," a vascular insufficiency condition characterized by numbness and tingling of the fingers, cold intolerance, "white-finger" attacks, and eventually even loss of fingers due to inadequate blood supply. OSHA does not set limits for vibration exposure, but the American National Standards Institute (ANSI) (2006) recommends that 8-hour workday exposures to hand-arm vibration (5 to 1400 Hz, summed over three orthogonal axes of movement) not exceed acceleration values of 2.5 m/s^2.

Excessive whole-body vibration is clearly linked to low back pain (Wilder, Wasserman, and Wasserman, 2002) and may contribute to gastrointestinal and urinary disorders, although these associations are not well established. ANSI (1979) recommends 8-hour limits for whole-body vibration of 0.3 m/s^2, for the body's most sensitive frequency range of 4 to 8 Hz. This is about 30 times more intense than the weakest vibration that people can detect (0.01 m/s^2).

Airborne sound can cause detectable body vibration, but this occurs only at very high levels—usually above sound pressure levels of 100 dB (unweighted) (Smith, 2002; Takahashi et al., 2005; Yamada et al., 1983). There is no scientific evidence to suggest that modern wind turbines cause perceptible vibration in homes or that there is an associated health risk.

3.4 Peer-Reviewed Literature Focusing on Wind Turbines, Low-Frequency Sound, and Infrasound

This section addresses the scientific review of the literature that has evaluated wind turbines, the annoyance effect, low frequency sound, and infrasound.

3.4.1 Evaluation of Annoyance and Dose-Response Relationship of Wind Turbine Sound

To date, three studies in Europe have specifically evaluated potential health effects of people living in proximity to wind turbines (Pedersen and Persson Waye, 2004; Pedersen and Persson Waye, 2007; Pedersen et al., 2009). These studies have been primarily in Sweden and the Netherlands. Customarily, an eligible group of people are selected for possible participation in the study based on their location with respect to a wind turbine. Control groups have not been included in any of these reports.

In an article published in August 2009, investigators reported the results of their evaluation of 725 people in the Netherlands, who lived in the vicinity of wind turbines (Pedersen et al., 2009). The potential study population consisted of approximately 70,000 people living within 2.5 kilometers of a wind turbine at selected sites in the Netherlands. The objective of the study was to (1) assess the relationship between wind turbine sound levels at dwellings and the probability of noise annoyance, taking into account possible moderating factors, and (2) explore the possibility of generalizing a dose response relationship for wind turbine noise by comparing the results of the study with previous studies in Sweden.

Noise impact was quantified based on the relationship between the sound level (dose) and response with the latter measured as the proportion of people annoyed or highly annoyed by sound. Prior to this study, dose response curves had been modeled for wind turbines. Previous studies have noted different degrees of relationships between wind turbine sound levels and annoyance (Wolsink et al., 1993; Pedersen and Persson Waye, 2004; Pedersen and Persson Waye, 2007).

Subjective responses were obtained through a survey. The calculation of the sound levels (dose) in Sweden and the Netherlands were similar. A dose response relationship was observed between calculated A-weighted sound pressure levels and annoyance. Sounds from wind turbines were found to be more annoying than several other environmental sources at comparable sound levels. A strong correlation was also noted between noise annoyance and negative opinion of the impact of wind turbines on the landscape, a finding in earlier studies as well. The dominant quality of the sound was a swishing, the quality previously found to be the most annoying type.

The authors concluded that this study could be used for calculating a dose response curve for wind turbine sound and annoyance. The study results suggest that wind turbine sound is easily perceived and, compared with sound from other sources, is annoying to a small percentage of people (5 percent at 35 to 40 dBA).

In this study, the proportion of people who reported being annoyed by wind turbine noise was similar to merged data from two previous Swedish studies (Pederson and Persson

Waye, 2004; Pedersen and Persson Waye, 2007). About 5 percent of respondents were annoyed at noise levels between 35 to 40 dBA and 18 percent at 40 to 45 dBA.

Pedersen et al. also reported significant dose responses between wind turbine sound and self-reported annoyance (Pedersen and Persson Waye, 2004). High exposed individuals responded more (78 percent) than low exposed individuals (60 percent), which suggests that bias could have played a role in the final results.

An analysis of two cross-sectional socio-acoustic studies—one that addressed flat landscapes in mainly rural settings (Pedersen and Persson Waye, 2004) and another in different terrains (complex or flat) and different levels of urbanization (rural or suburban) (Pedersen and Persson Waye, 2007)—was performed (Pedersen, 2008). Approximately 10 percent of over 1000 people surveyed via a questionnaire reported being very annoyed at sound levels of 40 dB and greater. Attitude toward the visual impact of the wind turbines had the same effect on annoyance. Response to wind turbine noise was significantly related to exposure expressed as A-weighted sound pressure levels dB. Among those who could hear wind turbine sound, annoyance with wind turbine noise was highly correlated to the sound characteristics: swishing, whistling, resounding and pulsating/throbbing (Pedersen, 2008).

A similar study in Sweden evaluated 754 people living near one of seven sites where wind turbine power was greater than 500 kilowatt (kW) (Pedersen and Persson Waye, 2007). Annoyance was correlated with sound level and also with negative attitude toward the visual impact of the wind turbines. Note that none of these studies included a control group. Earlier field studies performed among people living in the vicinity of wind turbines showed a correlation between sound pressure level and noise annoyance; however, annoyance was also influenced by visual factors and attitudes toward the impact of the wind turbines on the landscape. Noise annoyance was noted at lower sound pressure levels than annoyance from traffic noise. Although some people may be affected by annoyance, there is no scientific evidence that noise at levels created by wind turbines could cause health problems (Pedersen and Högskolan, 2003).

3.4.2 Annoyance

A feeling described as “annoyance” can be associated with acoustic factors such as wind turbine noise. There is considerable variability, however, in how people become “annoyed” by environmental factors such as road construction and aviation noise, among others (Leventhall, 2004). Annoyance is clearly a subjective effect that will vary among people and circumstances. In extreme cases, sleep disturbance may occur. Wind speed at the hub height of a wind turbine at night may be up to twice as high as during the day and may lead to annoyance from the amplitude modulated sound of the wind turbine (van den Berg, 2003). However, in a study of 16 sites in 3 European countries, only a weak correlation was noted between sound pressure level and noise annoyance from wind turbines (Pedersen and Högskolan, 2003).

In a detailed comparison of the role of noise sensitivity in response to environmental noise around international airports in Sydney, London, and Amsterdam, it was shown that noise sensitivity increases one’s perception of annoyance independently of the level of noise exposure (van Kamp et al., 2004).

In a Swedish study, 84 out of 1,095 people living in the vicinity of a wind turbine in 12 geographical areas reported being fairly or very annoyed by wind turbines (Pedersen, 2008). It is important to note that no differences were reported among people who were "annoyed" in contrast to those who were not annoyed with respect to hearing impairment, diabetes, or cardiovascular disease. An earlier study in Sweden showed that the proportion of people "annoyed" by wind turbine sound is higher than for other sources of environmental noise at the same decibel level (Pedersen and Persson Waye, 2004).

3.4.3 Low-Frequency Sound and Infrasound

No scientific studies have specifically evaluated health effects from exposure to low frequency sound from wind turbines. Natural sources of low frequency sound include wind, rivers, and waterfalls in both audible and non-audible frequencies. Other sources include road traffic, aircraft, and industrial machinery. The most common source of infrasound is vehicular (National Toxicology Program, 2001).

Infrasound at a frequency of 20 Hz (the upper limit of infrasound) is not detectable at levels lower than than 79 dB (Leventhall et al., 2003). Infrasound at 145 dB at 20 Hz and at 165 dB at 2 Hz can stimulate the auditory system and cause severe pain (Leventhall, 2006).These noise levels are substantially higher than any noise generated by wind turbines. The U.S. Food and Drug Administration (FDA) has approved the use of infrasound for therapeutic massage at 70 dB in the 8 to 14 Hz range (National Toxicology Program, 2001). In light of the FDA approval for this type of therapeutic use of infrasound, it is reasonable to conclude that exposure to infrasound in the 70 dB range is safe. According to a report of the National Research Council (NRC), low frequency sound is a concern for older wind turbines but not the modern type (National Research Council, 2007).

SECTION 4

Results

This section discusses the results of the anaylsis presented in Section 3. Potential effects from infrasound, low frequency sound, and the fluctuating aerodynamic "swish" from turbine blades are examined. Proposed hypotheses between wind turbine sound and physiological effects in the form of vibroacoustic disease, "wind turbine syndrome," and visceral vibratory vestibular disturbance are discussed.

4.1 Infrasound, Low-Frequency Sound, and Annoyance

Sound levels from wind turbines pose no risk of hearing loss or any other nonauditory effect. In fact, a recent review concluded that "Occupational noise-induced hearing damage does not occur below levels of 85 dBA." (Ising and Kruppa, 2004) The levels of sound associated with wind turbine operations are considerably lower than industry levels associated with noise induced hearing loss.

However, some people attribute certain health problems to wind turbine exposure. To make sense of these assertions, one must consider not only the sound but the complex factors that may lead to the perception of "annoyance." Most health complaints regarding wind turbines have centered on sound as the cause. There are two types of sounds from wind turbines: mechanical sound, which originates from the gearbox and control mechanisms, and the more dominant aerodynamical sound, which is present at all frequencies from the infrasound range over low frequency sound to the normal audible range.

Infrasound from natural sources (for example, ocean waves and wind) surrounds us and is below the audible threshold. The infrasound emitted from wind turbines is at a level of 50 to 70 dB, sometimes higher, but well below the audible threshold. There is a consensus among acoustic experts that the infrasound from wind turbines is of no consequence to health. One particular problem with many of these assertions about infrasound is that is that the term is often misused when the concerning sound is actually low frequency sound, not infrasound.

Under many conditions, low frequency sound below about 40 Hz cannot be distinguished from environmental background sound from the wind itself. Perceptible (meaning above both the background sound and the hearing threshold), low frequency sound can be produced by wind turbines under conditions of unusually turbulent wind conditions, but the actual sound level depends on the distance of the listener from the turbine, as the sound attenuates (falls off) with distance. The higher the frequency, the greater the sound attenuates with distance—Appendix D provides more information on the propagation of sound. The low frequency sound emitted by spinning wind turbines could possibly be annoying to some when winds are unusually turbulent, but there is no evidence that this level of sound could be harmful to health. If so, city dwelling would be impossible due to the similar levels of ambient sound levels normally present in urban environments. Nevertheless, a small number of people find city sound levels stressful.

It is not usually the low frequency nonfluctuating sound component, however, that provokes complaints about wind turbine sound. The fluctuating aerodynamic sound (swish) in the 500 to 1,000 Hz range occurs from the wind turbine blades disturbing the air, modulated as the blades rotate which changes the sound dispersion characteristics in an audible manner. This fluctuating aerodynamic sound is the cause of most sound complaints regarding wind turbines, as it is harder to become accustomed to fluctuating sound than to sound that does not fluctuate. However, this fluctuation does not always occur and a UK study showed that it had been a problem in only four out of 130 UK wind farms, and had been resolved in three of those (Moorhouse et al., 2007).

4.1.1 Infrasound and Low-Frequency Sound

Infrasound occurs at frequencies less than 20 Hz. At low and inaudible levels, infrasound has been suggested as a cause of "wind turbine syndrome" and vibroacoustic disease (VAD)—refer to Section 4.2.1 for more information on VAD. For infrasound to be heard, high sound levels are necessary (see Section 3, Table 3-2). There is little risk of short term acute exposure to high levels of infrasound. In experiments related to the Apollo space program, subjects were exposed to between 120 and 140 dB without known harmful effects. High level infrasound is less harmful than the same high levels of sound in the normal audible frequency range.

High levels of low frequency sound can excite body vibrations (Leventhall, 2003). Early attention to low frequency sound was directed to the U.S. space program, studies from which suggested that 24-hour exposures to 120 to 130 dB are tolerable below 20 Hz, the upper limit of infrasound. Modern wind turbines produce sound that is assessed as infrasound at typical levels of 50 to 70 dB, below the hearing threshold at those frequencies (Jakobsen, 2004). Jakobsen concluded that infrasound from wind turbines does not present a health concern. Fluctuations of wind turbine sound, most notably the swish-swish sounds, are in the frequency range of 500 to 1,000 Hz, which is neither low frequency sound nor infrasound. The predominant sound from wind turbines, however, is often mischaracterized as infrasound and low frequency sound. Levels of infrasound near modern-scale wind farms are in general not perceptible to people. In the human body, the beat of the heart is at 1 to 2 Hz. Higher-frequency heart sounds measured externally to the body are in the low frequency range (27 to 35 dB at 20 to 40 Hz), although the strongest frequency is that of the heartbeat (Sakai, Feigen, and Luisada, 1971). Lung sounds, measured externally to the body are in the range of 5 to 35 dB at 150 to 600 Hz (Fiz et al., 2008). Schust (2004) has given a comprehensive review of the effects of high level low frequency sound, up to 100 Hz.

4.1.2 Annoyance

Annoyance is a broad topic on which volumes have been written. Annoyance can be caused by constant amplitude and amplitude modulated sounds containing rumble (Bradley, 1994).

As the level of sound rises, an increasing number of those who hear it may become distressed, until eventually nearly everybody is affected, although to different degrees. This is a clear and easily understood process. However, what is not so clearly understood is that when the level of the sound reduces, so that very few people are troubled by it, there remain a small number who may be adversely affected. This occurs at all frequencies, although there seems to be more subjective variability at the lower frequencies. The effect of low

frequency sound on annoyance has recently been reviewed (Leventhall, 2004). The standard deviation of the hearing threshold is approximately 6 dB at low frequencies (Kurakata and Mizunami, 2008), so that about 2.5 percent of the population will have 12 dB more sensitive hearing than the average person. However, hearing sensitivity alone does not appear to be the deciding factor with respect to annoyance. For example, the same type of sound may elicit different reactions among people: one person might say "Yes, I can hear the sound, but it does not bother me," while another may say, "The sound is impossible, it is ruining my life." There is no evidence of harmful effects from the low levels of sound from wind turbines, as experienced by people in their homes. Studies have shown that peoples' attitudes toward wind turbines may affect the level of annoyance that they report (Pedersen et al., 2009).

Some authors emphasize the psychological effects of sounds (Kalveram, 2000; Kalveram et al., 1999). In an evaluation of 25 people exposed to five different wind turbine sounds at 40 dB, ratings of "annoyance" were different among different types of wind turbine noise (Persson Waye and Öhrström, 2002).

None of the psycho-acoustic parameters could explain the difference in annoyance responses. Another study of more than 2,000 people suggested that personality traits play a role in the perception of annoyance to environmental issues such as sound (Persson et al., 2007). Annoyance originates from acoustical signals that are not compatible with, or that disturb, psychological functions, in particular, disturbance of current activities. Kalveram et al. (1999) suggest that the main function of noise annoyance is as a warning that fitness may be affected but that it causes little or no physiological effect. Protracted annoyance, however, may undermine coping and progress to stress related effects. It appears that this is the main mechanism for effects on the health of a small number of people from prolonged exposure to low levels of noise.

The main health effect of noise stress is disturbed sleep, which may lead to other consequences. Work with low frequencies has shown that an audible low frequency sound does not normally become objectionable until it is 10 to 15 dB above hearing threshold (Inukai et al., 2000; Yamada, 1980). An exception is when a listener has developed hostility to the noise source, so that annoyance commences at a lower level.

There is no evidence that sound at the levels from wind turbines as heard in residences will cause direct physiological effects. A small number of sensitive people, however, may be stressed by the sound and suffer sleep disturbances.

4.1.3 Other Aspects of Annoyance

Some people have concluded that they have health problems caused directly by wind turbines. In order to make sense of these complaints, we must consider not only the sound, but the complex factors culminating in annoyance.

There is a large body of medical literature on stress and psychoacoustics. Three factors that may be pertinent to a short discussion of wind turbine annoyance effects are the nocebo effect, sensory integration dysfunction and somatoform disorders.

4.1.4 Nocebo Effect

The nocebo effect is an adverse outcome, a worsening of mental or physical health, based on fear or belief in adverse effects. This is the opposite of the well known placebo effect, where belief in positive effects of an intervention may produce positive results (Spiegel, 1997). Several factors appear to be associated with the nocebo phenomenon: expectations of adverse effects; conditioning from prior experiences; certain psychological characteristics such as anxiety, depression and the tendency to somatize (express psychological factors as physical symptoms; see below), and situational and contextual factors. A large range of reactions include hypervagotonia, manifested by idioventricular heart rhythm (a slow heart rate of 20 to 50 beats per minute resulting from an intrinsic pacemaker within the ventricles which takes over when normal sinoatrial node regulation is lost), drowsiness, nausea, fatigue, insomnia, headache, weakness, dizziness, gastrointestinal (GI) complaints and difficulty concentrating (Sadock and Sadock, 2005, p.2425). This array of symptoms is similar to the so-called "wind turbine syndrome" coined by Pierpont (2009, pre-publication draft). Yet these are all common symptoms in the general population and no evidence has been presented that such symptoms are more common in persons living near wind turbines. Nevertheless, the large volume of media coverage devoted to alleged adverse health effects of wind turbines understandably creates an anticipatory fear in some that they will experience adverse effects from wind turbines. Every person is suggestible to some degree. The resulting stress, fear, and hypervigilance may exacerbate or even create problems which would not otherwise exist. In this way, anti-wind farm activists may be creating with their publicity some of the problems that they describe.

4.1.5 Somatoform Disorders

There are seven somatoform disorders in the Fourth Edition of *Diagnostic and Statistical Manual of Mental Disorders* (DSM-IV-TR) (American Psychiatric Association, 2000). Somatoform disorders are physical symptoms which reflect psychological states rather than arising from physical causes. One common somatoform disorder, Conversion Disorder, is the unconscious expression of stress and anxiety as one or more physical symptoms (Escobar and Canino, 1989). Common conversion symptoms are sensations of tingling or discomfort, fatigue, poorly localized abdominal pain, headaches, back or neck pain, weakness, loss of balance, hearing and visual abnormalities. The symptoms are not feigned and must be present for at least six months according to DSM-IV-TR and two years according to the International Statistical Classification of Diseases and Related Health Problems, 10th Revision (ICD-10) (WHO, 1993). ICD-10 specifies the symptoms as belonging to four groups: (1) Gastrointestinal (abdominal pain, nausea, bloating/gas/, bad taste in mouth/excessive tongue coating, vomiting/regurgitation, frequent/loose bowel movements); (2) Cardiovascular (breathlessness without exertion, chest pains); (3) Genitourinary (frequency or dysuria, unpleasant genital sensations, vaginal discharge), and (4) Skin and Pain (blotchiness or discoloration of the skin, pain in the limbs, extremities or joints, paresthesias). ICD-10 specifies that at least six symptoms must be present in two or more groups.

One feature of somatoform disorders is *somatosensory amplification*, a process in which a person learns to feel body sensations more acutely and may misinterpret the significance of those sensations by equating them with illness (Barsky, 1979). *Sensory integration dysfunction*

describes abnormal sensitivity to any or all sensory stimuli (sound, touch, light, smell, and taste). There is controversy among researchers and clinicians as to whether sensory integration problems exist as an independent entity or as components of a pervasive developmental disorder (Sadock and Sadock, 2005, p. 3135), but their presence can lead to overestimation of the likelihood of being ill (Sadock and Sadock, 2005, p. 1803). Sensory integration dysfunction as such is not listed in the DSM-IV-TR or in the ICD-10.

Day-to-day stressors and adverse life events provide multiple stimuli to which people respond, and that response is often somatic due to catecholamines and activation of the autonomic nervous system. This stress response can become conditioned as memory. There is some evidence that poor coping mechanisms (anger impulsivity, hostility, isolation, lack of confiding in others) are linked to physiological reactivity, which is associated with somatic sensation and amplification (Sadock and Sadock, 2005, p. 1806).

In summary, the similarities of common human stress responses and conversion symptoms to those described as "wind turbine syndrome" are striking. An annoyance factor to wind turbine sounds undoubtedly exists, to which there is a great deal of individual variability. Stress has multiple causes and is additive. Associated stress from annoyance, exacerbated by the rhetoric, fears, and negative publicity generated by the wind turbine controversy, may contribute to the reported symptoms described by some people living near rural wind turbines.

4.2 Infrasound, Low-frequency Sound and Disease

Some reports have suggested a link between low frequency sound from wind turbines and certain adverse health effects. A careful review of these reports, however, leads a critical reviewer to question the validity of the claims for a number of reasons, most notably (1) the level of sound exposure associated with the putative health effects, (2) the lack of diagnostic specificity associated with the health effects reported, and (3) the lack of a control group in the analysis.

4.2.1 Vibroacoustic Disease

Vibroacoustic disease (VAD) in the context of exposure of aircraft engine technicians to sound was defined by Portuguese researchers as a whole-body, multi-system entity, caused by chronic exposure to large pressure amplitude and low frequency (LPALF) sound (Alves-Pereira and Castelo Branco, 2007a; Alves-Pereira and Castelo Branco, 2007b; Alves-Pereira and Castelo Branco, 2007c; Alves-Pereira and Castelo Branco, 2007d). VAD, the primary feature of which is thickening of cardiovascular structures, such as cardiac muscle and blood vessels, was first noted among airplane technicians, military pilots, and disc jockeys (Maschke, 2004; Castelo Branco, 1999). Workers had been exposed to high levels for more than 10 years. There are no epidemiological studies that have evaluated risk of VAD from exposure to infrasound. The likelihood of such a risk, however, is remote in light of the much lower vibration levels in the body itself. Studies of workers with substantially higher exposure levels have not indicated a risk of VAD. VAD has been described as leading from initial respiratory infections, through pericardial thickening to severe and life-threatening illness such as stroke, myocardial infarction, and risk of malignancy (Alves-Pereira and Castelo Branco, 2007a).

4.2.2 High-Frequency Exposure

All of the exposures of subjects for whom the VAD concept was developed, were dominated by higher frequency sounds, a critical point since the frequency range claimed for VAD-inducing sound is much wider than the frequency range of exposures experienced by the aircraft technicians who were diagnosed with VAD (Castelo Branco, 1999). Originally, proponents of the VAD concept had proposed a "greater than 90 dB" criterion for VAD. However, now some claim that VAD will result from exposure to almost any level of infrasound and low frequency sound at any frequency below 500 Hz. This assertion is an extraordinary extrapolation given that the concept of VAD developed from observations that a technician, working around military aircraft on the ground, with engines operating, displayed disorientation (Castelo Branco, 1999). Sound levels near aircraft were very high. In an evaluation of typical engine spectra of carrier based combat aircraft operating on the ground, the spectra peaked at frequencies above 100 Hz with sound levels from 120 to 135 dB close to the aircraft (Smith, 2002). The levels drop considerably, however, into the low frequency region.

There is an enormous decibel difference between the sound exposure of aircraft technicians and the sound exposure of people who live near wind turbines. Animal experiments indicated that exposure levels necessary to cause VAD were 13 weeks of continuous exposure to approximately 100 dB of low frequency sound (Mendes et al., 2007). The exposure levels were at least 50 to 60 dB higher than wind turbine levels in the same frequency region (Hayes, 2006a).

4.2.3 Residential Exposure: A Case Series

Extrapolation of results from sound levels greater than 90 dB and at predominantly higher frequencies (greater than 100 Hz) to a risk of VAD from inaudible wind turbine sound levels of 40 to 50 dB in the infrasound region, is a new hypothesis. One investigator, for example, has claimed that wind turbines in residential areas produce acoustical environments that can lead to the development of VAD in nearby home-dwellers (Alves-Pereira and Castelo Branco, 2007a).

This claim is based on comparison of only two infrasound exposures. The first is for a family which has experienced a range of health problems and which also complained of disturbances from low frequency sound. The second is for a family which lived near four wind turbines, about which they have become anxious (Alves-Pereira and Castelo Branco, 2007a; Alves-Pereira and Castelo Branco, 2007b).

The first family (Family F), was exposed to low levels of infrasound consisting of about 50 dB at 8 Hz and 10 Hz from a grain terminal about 3 kilometers (km) away and additional sources of low frequency sound, including a nearer railway line and road. The second family (Family R) lives in a rural area and was described as exposed to infrasound levels of about 55 dB to 60 dB at 8 Hz to 16 Hz. These exposures are well below the hearing threshold and not uncommon in urban areas. Neither the frequency nor volume of the sound exposures experienced by Families F or R are unusual. Exposure to infrasound (< 20 Hz) did not exceed 50 dB.

4.2.3.1 Family F—Exposure to Low Levels of Infrasound

Family F has a long history of poor health and a 10-year-old boy was diagnosed with VAD due to exposure to infrasound from the grain terminal (Alves-Pereira and Castelo Branco, 2007a; Castelo Branco et al., 2004). However, the infrasound levels are well below hearing threshold and are typical of urban infrasound, which occurs widely and to which many people are exposed.

According to the authors, the main effect of VAD was demonstrated by the 10-year-old boy in the family, as pericardial thickening.[3] However, the boy has a history of poor health of unknown etiology (Castelo Branco et al., 2004). Castelo Branco (1999) has defined pericardial thickening as an indicator of VAD and assumes that the presence of pericardial thickening in the boy from Family F must be an effect of VAD, caused by exposure to the low-level, low frequency sound from the grain terminal. This assumption excludes other possible causes of pericardial thickening, including viral infection, tuberculosis, irradiation, hemodialysis, neoplasia with pericardial infiltration, bacterial, fungal, or parasitic infections, inflammation after myocardial infarction, asbestosis, and autoimmune diseases. The authors did not exclude these other possible causes of pericardial thickening.

4.2.3.2 Family R—Proximity to Turbines and Anxiety

Family R, living close to the wind turbines, has low frequency sound exposure similar to that of Family F. The family does not have symptoms of VAD, but it was claimed that "Family R. will also develop VAD should they choose to remain in their home." (Alves-Pereira and Castelo Branco, 2007b). In light of the absence of literature of cohort and case control studies, this bold statement seems to be unsubstantiated by available scientific literature.

4.2.4 Critique

It appears that Families F and R were self-selected complainants. Conclusions derived by Alves-Pereira and Castelo Branco (2007b) have been based only on the poor health and the sound exposure of Family F, using this single exposure as a measure of potential harmful effects for others. There has been no attempt at an epidemiological study.

Alves-Pereira and Castelo Branco claim that exposure at home is more significant than exposure at work because of the longer periods of exposure (Alves-Pereira and Castelo Branco, 2007e). Because an approximate 50 dB difference occurs between the exposure from wind turbines and the exposure that induced VAD (Hayes, 2006a), it will take 10^5 years (100,000 years) for the wind turbine dose to equal that of one year of the higher level sound.

Among published scientific literature, this description of the two families is known as a case series, which are of virtually no value in understanding potential *causal associations* between exposure to a potential hazard (i.e., low frequency sound) and a potential health effect (i.e., vibroacoustic disease). Case reports have value but primarily in generating hypotheses to test in other studies such as large groups of people or in case control studies. The latter type of study can systematically evaluate people with pericardial thickening who live near wind turbines in comparison to people with pericardial thickening who do not live

[3] Pericardial thickening is unusual thickening of the protective sac (pericardium) which surrounds the heart. For example, see http://www.emedicine.com/radio/topic191.htm.

near wind turbines. Case reports need to be confirmed in larger studies, most notably cohort studies and case-control studies, before definitive cause and effect assertions can be drawn. The reports of the two families do not provide persuasive scientific evidence of a link between wind turbine sound and pericardial thickening.

Wind turbines produce low levels of infrasound and low frequency sound, yet there is no credible scientific evidence that these levels are harmful. If the human body is affected by low, sub-threshold sound levels, a unique and not yet discovered receptor mechanism of extraordinary sensitivity to sound is necessary—a mechanism which can distinguish between the normal, relatively high-level "sound" inherent in the human body[4] and excitation by external, low-level sound. Essential epidemiological studies of the potential effects of exposure at low sound levels at low frequencies have not been conducted. Until the fuzziness is clarified, and a receptor mechanism revealed, no reliance can be placed on the case reports that the low levels of infrasound and low frequency sound are a cause of vibroacoustic disease.[5]

The attribution of dangerous properties to low levels of infrasound continues unproven, as it has been for the past 40 years. No foundation has been demonstrated for the new hypothesis that exposure to sub-threshold, low levels of infrasound will lead to vibroacoustic disease. Indeed, human evolution has occurred in the presence of natural infrasound.

4.3 Wind Turbine Syndrome

"Wind turbine syndrome" as promoted by Pierpont (2009, pre-publication draft) appears to be based on the following two hypotheses:

1. Low levels of airborne infrasound from wind turbines, at 1 to 2 Hz, directly affect the vestibular system.

2. Low levels of airborne infrasound from wind turbines at 4 to 8 Hz enter the lungs via the mouth and then vibrate the diaphragm, which transmits vibration to the viscera, or internal organs of the body.

The combined effect of these infrasound frequencies sends confusing information to the position and motion detectors of the body, which in turn leads to a range of disturbing symptoms.

4.3.1 Evaluation of Infrasound on the Vestibular System

Consider the first hypothesis. The support for this hypothesis is a report apparently misunderstood to mean that the vestibular system is more sensitive than the cochlea to low levels of both sound and vibration (Todd et al., 2008a). The Todd report is concerned with vibration input to the mastoid area of the skull, and the corresponding detection of these vibrations by the cochlea and vestibular system. The lowest frequency used was 100 Hz,

[4] Body sounds are often used for diagnosis. For example see Gross, V., A. Dittmar, T. Penzel, F., Schüttler, and P. von Wichert.. (2000): "The Relationship between Normal Lung Sounds, Age, and Gender. " *American Journal of Respiratory and Critical Care Medicine*. Volume 162, Number 3: 905 - 909.

[5] This statement should not be interpreted as a criticism of the work of the VAD Group with aircraft technicians at high noise levels.

considerably higher than the upper limit of the infrasound frequency (20 Hz). The report does not address air-conducted sound or infrasound, which according to Pierpont excites the vestibular system by airborne sound and by skull vibration. This source does not support Pierpont's hypothesis and does not demonstrate the points that she is trying to make.

There is no credible scientific evidence that low levels of wind turbine sound at 1 to 2 Hz will directly affect the vestibular system. In fact, it is likely that the sound will be lost in the natural infrasonic background sound of the body. The second hypothesis is equally unsupported with appropriate scientific investigations. The body is a noisy system at low frequencies. In addition to the beating heart at a frequency of 1 to 2 Hz, the body emits sounds from blood circulation, bowels, stomach, muscle contraction, and other internal sources. Body sounds can be detected externally to the body by the stethoscope.

4.3.2 Evaluation of Infrasound on Internal organs

It is well known that one source of sound may mask the effect of another similar source. If an external sound is detected within the body in the presence of internally generated sounds, the external sound must produce a greater effect in the body than the internal sounds. The skin is very reflective at higher frequencies, although the reflectivity reduces at lower frequencies (Katz, 2000). Investigations at very low frequencies show a reduction of about 30 dB from external to internal sound in the body of a sheep (Peters et al., 1993). These results suggest an attenuation (reduction) of low frequency sound by the body before the low frequency sound reaches the internal organs.

Low-level sounds from outside the body do not cause a high enough excitation within the body to exceed the internal body sounds. Pierpont refers to papers from Takahashi and colleagues on vibration excitation of the head by high levels of external sound (over 100 dB). However, these papers state that response of the head at frequencies below 20 Hz was not measurable due to the masking effect of internal body vibration (Takahashi et al., 2005; Takahashi et al., 1999). When measuring chest resonant vibration caused by external sounds, the internal vibration masks resonance for external sounds below 80 dB excitation level (Leventhall, 2006). Thus, the second hypothesis also fails.

To recruit subjects for her study, Pierpont sent out a general call for anybody believing their health had been adversely affected by wind turbines. She asked respondents to contact her for a telephone interview. The case series results for ten families (37 subjects) are presented in Pierpont (2009, pre-publication draft). Symptoms included sleep disturbance, headache, tinnitus, ear pressure, vertigo, nausea, visual blurring, tachycardia, irritability, concentration, memory, panic attacks, internal pulsation, and quivering. This type of study is known as a case series. A case series is of limited, if any, value in evaluating causal connections between an environmental exposure (in this case, sound) and a designated health effect (so called "wind turbine syndrome"). This particular case series is substantially limited by selection bias, in which people who already think that they have been affected by wind turbines "self select" to participate in the case series. This approach introduces a significant bias in the results, especially in the absence of a control group who do not live in proximity of a wind turbine. The results of this case series are at best hypothesis-generating activities that do not provide support for a causal link between wind turbine sound and so-called "wind turbine syndrome."

However, these so called "wind turbine syndrome" symptoms are not new and have been published previously in the context of "annoyance" to environmental sounds (Nagai et al., 1989; Møller and Lydolf, 2002; Mirowska and Mroz, 2000). The following symptoms are based on the experience of noise sufferers extending over a number of years: distraction, dizziness, eye strain, fatigue, feeling vibration, headache, insomnia, muscle spasm, nausea, nose bleeds, palpitations, pressure in the ears or head, skin burns, stress, and tension (Leventhall, 2002).

The symptoms are common in cases of extreme and persistent annoyance, leading to stress responses in the affected individual and may also result from severe tinnitus, when there is no external sound. The symptoms are exhibited by a small proportion of sensitive persons and may be alleviated by a course of psychotherapy, aimed at desensitization from the sound (Leventhall et al., 2008). The similarity between the symptoms of noise annoyance and those of "wind turbine syndrome" indicates that this "diagnosis" is not a pathophysiological effect, but is an example of the well-known stress effects of exposure to noise, as displayed by a small proportion of the population. These effects are familiar to environmental noise control officers and other "on the ground" professionals.

"Wind turbine syndrome," not a recognized medical diagnosis, is essentially reflective of symptoms associated with noise annoyance and is an unnecessary and confusing addition to the vocabulary on noise. This syndrome is not a recognized diagnosis in the medical community. There are no unique symptoms or combinations of symptoms that would lead to a specific pattern of this hypothesized disorder. The collective symptoms in some people exposed to wind turbines are more likely associated with annoyance to low sound levels.

4.4 Visceral Vibratory Vestibular Disturbance

4.4.1 Hypothesis

In addition to case reports of symptoms reported by people who live near wind turbines, Pierpont has proposed a hypothesis that purports to explain how some of these symptoms arise: visceral vibratory vestibular disturbance (VVVD) (Pierpont, 2009, pre-publication draft). VVVD has been described as consisting of vibration associated with low frequencies that enters the body and causes a myriad of symptoms. Pierpont considers VVVD to be the most distinctive feature of a nonspecific set of symptoms that she describes as "wind turbine syndrome." As the name VVVD implies, wind turbine sound in the 4 to 8 Hz spectral region is hypothesized to cause vibrations in abdominal viscera (e.g., intestines, liver, and kidneys) that in turn send neural signals to the part of the brain that normally receives information from the vestibular labyrinth. These signals hypothetically conflict with signals from the vestibular labyrinth and other sensory inputs (visual, proprioceptive), leading to unpleasant symptoms, including panic. Unpleasant symptoms (especially nausea) can certainly be caused by sensory conflict; this is how scientists explain motion sickness. However, this hypothesis of VVVD is implausible based on knowledge of sensory systems and the energy needed to stimulate them. Whether implausible or not, there are time-tested scientific methods available to evaluate the legitimacy of any hypothesis and at this stage, VVVD as proposed by Pierpont is an untested hypothesis. A case series of 10 families recruited to participate in a study based on certain symptoms would not be considered evidence of causality by research or policy institutions such as the International Agency for Research on

Cancer (IARC) or EPA. As noted earlier in this report, a case series of self-selected patients does not constitute evidence of a causal connection.

4.4.2 Critique

Receptors capable of sensing vibration are located predominantly in the skin and joints. A clinical neurological examination normally includes assessment of vibration sensitivity. It is highly unlikely, however, that airborne sound at comfortable levels could stimulate these receptors, because most of airborne sound energy is reflected away from the body. Takahashi et al. (2005) used airborne sound to produce chest or abdominal vibration that exceeded ambient body levels. This vibration may or may not have been detectable by the subjects. Takahashi found that levels of 100 dB sound pressure level were required at 20 to 50 Hz (even higher levels would have been required at lower and higher frequencies). Sounds like this would be considered by most people to be very loud, and are well beyond the levels produced by wind turbines at residential distances. Comparison of the responses to low frequency airborne sound by normal hearing and profoundly deaf persons has shown that deaf subjects can detect sound transmitted through their body only when it is well above the normal hearing threshold (Yamada et al., 1983). For example, at 16 Hz, the deaf persons' average threshold was 128 dB sound pressure level, 40 dB higher than that of the hearing subjects. It has also been shown that, at higher frequencies, the body surface is very reflective of sound (Katz, 2000). Similarly, work on transmission of low frequency sound into the bodies of sheep has shown a loss of about 30 dB (Peters et al., 1993)

The visceral receptors invoked as a mechanism for VVVD have been shown to respond to static gravitational position changes, but not to vibration (that is why they are called graviceptors). If there were vibration-sensitive receptors in the abdominal viscera, they would be constantly barraged by low frequency body sounds such as pulsatile blood flow and bowel sounds, while external sounds would be attenuated by both the impedance mismatch and dissipation of energy in the overlying tissues. Finally, wind turbine sound at realistic distances possesses little, if any, acoustic energy, at 4 to 8 Hz.

It has been hypothesized that the vestibular labyrinth may be "abnormally stimulated" by wind turbine sound (Pierpont, 2009, pre-publication draft). As noted in earlier sections of this report, moderately loud airborne sound, at frequencies up to about 500 Hz, can indeed stimulate not only the cochlea (the hearing organ) but also the otolith organs. This is not abnormal, and there is no evidence in the medical literature that it is in any way unpleasant or harmful. In ordinary life, most of us are exposed for hours every day to sounds louder than those experienced at realistic distances from wind turbines, with no adverse effects. This assertion that the vestibular labyrinth is stimulated at levels below hearing threshold is based on a misunderstanding of research that used bone-conducted vibration rather than airborne sound. Indeed, those who wear bone conduction hearing aids experience constant stimulation of their vestibular systems, in addition to the cochlea, without adverse effects.

4.5 Interpreting Studies and Reports

In light of the unproven hypotheses that have been introduced as reflective of adverse health effects attributed to wind turbines, it can be instructive to review the type of research studies that can be used to determine definitive links between exposure to an environmental

hazard (in this case, sound and vibration emissions from wind turbines) and adverse health effects (the so-called "wind turbine syndrome").

How do we know, for example, that cigarettes cause lung cancer and that excessive noise causes hearing loss? Almost always, the first indication that an exposure might be harmful comes from the informal observations of doctors who notice a possible correlation between an exposure and a disease, then communicate their findings to colleagues in case reports, or reports of groups of cases (*case series*). These initial observations are usually uncontrolled; that is, there is no comparison of the people who have both exposure and disease to control groups of people who are either non-exposed or disease-free. There is usually no way to be sure that the apparent association is statistically significant (as opposed to simple coincidence), or that there is a causal relationship between the exposure and the disease in question, without control subjects. For these reasons, case reports and case series cannot prove that an exposure is really harmful, but can only help to develop hypotheses that can then be tested in controlled studies (Levine et al., 1994; Genovese, 2004; McLaughlin, 2003).

Once suspicion of harm has been raised, controlled studies (case-control or cohort) are essential to determine whether or not a causal association is likely, and only after multiple independent-controlled studies show consistent results is the association likely to be broadly accepted (IARC, 2006).

Case-control studies compare people with the disease to people without the disease (ensuring as far as possible that the two groups are well-matched with respect to all other variables that might affect the chance of having the disease, such as age, sex, and other exposures known to cause the disease). If the disease group is found to be much more likely to have had the exposure in question, and if multiple types of error and bias can be excluded (Genovese, 2004), a causal link is likely. Multiple case-control studies were necessary before the link between smoking and lung cancer could be proved.

Cohort studies compare people with the exposure to well-matched control subjects who have not had that exposure. If the exposed group proves to be much more likely to have the disease, assuming error and bias can be excluded, a causal link is likely. After multiple cohort studies, it was clear that excessive noise exposure caused hearing loss (McCunney and Meyer, 2007).

In the case of wind turbine noise and its hypothetical relationships to "wind turbine syndrome" and vibroacoustic disease, the weakest type of evidence—case series—is available, from only a single investigator. These reports can do no more than suggest hypotheses for further research. Nevertheless, if additional and independent investigators begin to report adverse health effects in people exposed to wind turbine noise, in excess of those found in unexposed groups, and if some consistent syndrome or set of symptoms emerges, this advice could change. Thus, at this time, "wind turbine syndrome" and VVVD are unproven hypotheses (essentially unproven ideas) that have not been confirmed by appropriate research studies, most notably cohort and case control studies. However, the weakness of the basic hypotheses makes such studies unlikely to proceed.

4.6 Standards for Siting Wind Turbines

4.6.1 Introduction

While the use of large industrial-scale wind turbines is well established in Europe, the development of comparable wind energy facilities in North America is a more recent occurrence. The growth of wind and other renewable energy sources is expected to continue. Opponents of wind energy development argue that the height and setback regulations established in some jurisdictions are too lenient and that the noise limits which are applied to other sources of noise (either industrial or transportation) are not sufficient for wind turbines for a variety of reasons. Therefore, they are concerned that the health and well-being of some residents who live in the vicinity (or close proximity to) of these facilities is threatened. Critics maintain that wind turbine noise may present more than an annoyance to nearby residents especially at night when ambient levels may be low. Consequently, there are those who advocate for a revision of the existing regulations for noise and setback pertaining to the siting of wind installations (Kamperman and James, 2009). Some have indicated their belief that setbacks of more than 1 mile may be necessary. While the primary purpose of this study was to evaluate the potential for adverse health effects rather than develop public policy, the panel does not find that setbacks of 1 mile are warranted.

4.6.2 Noise Regulations and Ordinances

In 1974, EPA published a report that examined the levels of environmental noise necessary to protect public health and welfare (EPA, 1974). Based on the analysis of available scientific data, EPA specified a range of day-night sound levels necessary to protect the public health and welfare from the effects of environmental noise, with a reasonable margin of safety. Rather than establishing standards or regulations, however, EPA simply identified noise levels below which the general public would not be placed at risk from any of the identified effects of noise. Each federal agency has developed its own noise criteria for sources for which they have jurisdiction (i.e., the Federal Aviation Administration regulates aircraft and airport noise, the Federal Highway Administration regulates highway noise, and the Federal Energy Regulatory Commission regulates interstate pipelines (Bastasch, 2005). State and local governments were provided guidance by EPA on how to develop their own noise regulations, but the establishment of appropriate limits was left to local authorities to determine given each community's differing values and land use priorities (EPA, 1975).

4.6.3 Wind Turbine Siting Guidelines

Establishing appropriate noise limits and setback distances for wind turbines has been a concern of many who are interested in wind energy. There are several approaches to regulating noise, from any source, including wind turbines. They can generally be classified as absolute or relative standards or a combination of absolute and relative standards. Absolute standards establish a fixed limit irrespective of existing noise levels. For wind turbines, a single absolute limit may be established regardless of wind speed (i.e., 50 dBA) or different limits may be established for various wind speeds (i.e., 40 dBA at 5 meters per second [m/s] and 45 dBA at 8 m/s). The Ontario Ministry of Environment (2008) wind turbine noise guidelines is an example of fixed limits for each integer wind speed between 4 and 10 meters per second. Relative standards limit the increase over existing levels and may

also establish either an absolute floor or ceiling beyond which the relative increase is not considered. That is, for example, if a relative increase of 10 dBA with a ceiling of 50 dBA is allowed and the existing level is 45 dBA, a level of 55 dBA would not be allowed. Similarly, if a floor of 40 dBA was established and the existing level is 25 dBA, 40 dBA rather than 35 dBA would be allowed. Fixed distance setbacks have also been discussed. Critics of this approach suggest that fixed setbacks do not take into account the number or size of the turbines nor do they consider other potential sources of noise within the project area. It is clear that like many other sources of noise, a uniform regulator approach for wind turbine noise has not been established either domestically or internationally.

A draft report titled *Environmental Noise and Health in the UK,* published for comment in 2009 by the Health Protection Agency (HPA) on behalf of an ad hoc expert group, provides insightful comments on the World Health Organization's noise guidelines (WHO, 1999). The HPA draft report can be viewed at the following address:

http://www.hpa.org.uk/web/HPAwebFile/HPAweb_C/1246433634856

The HPA report states the following:

It is important to bear in mind that the WHO guideline values, like other WHO guidelines, are offered to policymakers as a contribution to policy development. They are not intended as standards in a formal sense but as a possible basis for the development of standards. By way of overall summary, the 1998 NPL report noted [a British report titled *Health-Based Noise Assessment Methods—A Review and Feasibility Study* (Porter et al., 1998) as quoted in HPA 2009]:

> *The WHO guidelines represent a consensus view of international expert opinion on the lowest noise levels below which the occurrence rates of particular effects can be assumed to be negligible. Exceedances of the WHO guideline values do not necessarily imply significant noise impact and indeed, it may be that significant impacts do not occur until much higher degrees of noise exposure are reached. The guidelines form a starting point for policy development. However, it will clearly be important to consider the costs and benefits of reducing noise levels and, as in other areas, this should inform the setting of objectives.*
> (From: HPA, 2009, p. 77)

The HPA report further states the following:

> *Surveys have shown that about half of the UK population lives in areas where daytime sound levels exceed those recommended in the WHO Community Noise Guidelines. About two-thirds of the population live in areas where the night-time guidelines recommended by WHO are exceeded. (p. 81)*
>
> *That sleep can be affected by noise is common knowledge. Defining a dose-response curve that describes the relationship between exposure to noise and sleep disturbance has, however, proved surprisingly difficult. Laboratory studies and field studies have generated different results. In part this is due to habituation to noise which, in the field, is common in many people. (p. 82)*
>
> *Our examination of the evidence relating to the effects of environmental noise on health has demonstrated that this is a rapidly developing area. Any single report will, therefore, need to be revised within a few years. We conclude and recommend that an*

> *independent expert committee to address these issues on a long-term basis be established. (p. 82)*

The statements cited above from the HPA and WHO documents address general environmental noise concerns rather than concerns focused solely on wind turbine noise.

SECTION 5

Conclusions

Many countries have turned to wind energy as a key strategy to generate power in an environmentally clean manner. Wind energy enjoys considerable public support, but it has its detractors, who have publicized their concerns that the sounds emitted from wind turbines cause adverse health consequences.

The objective of the panel was to develop an authoritative reference document for the use of legislators, regulators, and citizens simply wanting to make sense of the conflicting information about wind turbine sound. To this end, the panel undertook extensive review, analysis, and discussion of the peer-reviewed literature on wind turbine sound and possible health effects. The varied professional backgrounds of panel members (audiology, acoustics, otolaryngology, occupational and environmental medicine, and public health) were highly advantageous in creating a diversity of informed perspectives. Participants were able to examine issues surrounding health effects and discuss plausible biological effects with considerable combined expertise.

Following review, analysis, and discussion, the panel reached agreement on three key points:

- There is nothing unique about the sounds and vibrations emitted by wind turbines.
- The body of accumulated knowledge about sound and health is substantial.
- The body of accumulated knowledge provides no evidence that the audible or subaudible sounds emitted by wind turbines have any direct adverse physiological effects.

The panel appreciated the complexities involved in the varied human reactions to sound, particularly sounds that modulate in intensity or frequency. Most complaints about wind turbine sound relate to the aerodynamic sound component (the swish sound) produced by the turbine blades. The sound levels are similar to the ambient noise levels in urban environments. A small minority of those exposed report annoyance and stress associated with noise perception.

This report summarizes a number of physical and psychological variables that may influence adverse reactions. In particular, the panel considered “wind turbine syndrome” and vibroacoustic disease, which have been claimed as causes of adverse health effects. The evidence indicates that “wind turbine syndrome” is based on misinterpretation of physiologic data and that the features of the so-called syndrome are merely a subset of annoyance reactions. The evidence for vibroacoustic disease (tissue inflammation and fibrosis associated with sound exposure) is extremely dubious at levels of sound associated with wind turbines.

The panel also considered the quality of epidemiologic evidence required to prove harm. In epidemiology, initial case reports and uncontrolled observations of disease associations

need to be confirmed through controlled studies with case-control or cohort methodology before they can be accepted as reflective of casual connections between wind turbine sound and health effects. In the area of wind turbine health effects, no case-control or cohort studies have been conducted as of this date. Accordingly, allegations of adverse health effects from wind turbines are as yet unproven. Panel members agree that the number and uncontrolled nature of existing case reports of adverse health effects alleged to be associated with wind turbines are insufficient to advocate for funding further studies.

In conclusion:

1. Sound from wind turbines does not pose a risk of hearing loss or any other adverse health effect in humans.
2. Subaudible, low frequency sound and infrasound from wind turbines do not present a risk to human health.
3. Some people may be annoyed at the presence of sound from wind turbines. Annoyance is not a pathological entity.
4. A major cause of concern about wind turbine sound is its fluctuating nature. Some may find this sound annoying, a reaction that depends primarily on personal characteristics as opposed to the intensity of the sound level.

SECTION 6

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APPENDIX A
Fundamentals of Sound

APPENDIX A

Fundamentals of Sound

The following appendix provides additional background information on sound and how it is defined.

One atmospheric pressure is given by 100,000 pascals (Pa), where one pascal is one Newton per square meter (N/m^2), and a sound pressure of 94 dB re 20μPa is given by 1 Pa (See later for decibels). The frequency of the fluctuations may be between 20 times a second (20 Hz), and up to 20,000 times a second (20,000 Hz) for the "audible" noise. Frequencies below 20 Hz are commonly called "infrasound," although there is a very fuzzy boundary between infrasound and low frequency noise. Infrasound at high levels is audible. Low frequency noise might be from about 10 Hz to about 200 Hz.

In addition to frequency, the quantities which define a sound wave include:

- Pressure, P
- Wavelength, λ
- Velocity, c = 340m/s approx, depending on temperature

The velocity and wavelength are related by: velocity = wavelength x frequency,

Relating frequency and wavelength by velocity gives

Freq Hz	16	31.5	63	125	250	500	1000	2000	4000
Wavelength m	21	11	5.4	2.7	1.4	0.68	0.34	0.17	0.085

Low frequencies have long wavelengths. It is useful to develop an appreciation of frequencies and related wavelengths, since this helps an understanding of noise propagation and control.

Sound pressure in a wave is force per unit of area of the wave and has units of N/m^2, which is abbreviated to Pa. The sound pressure fluctuates above and below atmospheric pressure by a very small amount.

The sound power is a characteristic of the source, and is its rate of production of energy, expressed in watts. The sound power is the fundamental property of the source, whilst the sound pressure at a measurement location depends on the transmission path from source to receiver. Most sound sources, including wind turbines, are specified in terms of their sound power. The sound power of a wind turbine is typically in the 100-105 dBA range, which is similar to that of a leaf blower. The sound power is used to predict propagation of the sound, where the source is assumed to be at the hub.

Sound Levels

The decibel is the logarithm of the ratio between two values of a quantity such as power, pressure or intensity, with a multiplying constant to give convenient numerical factors. Logarithms are useful for compressing a wide range of quantities into a smaller range. For example:

$\log_{10}10 = 1$
$\log_{10}100 = 2$
$\log_{10}1000 = 3$

The ratio of 1000:10 is compressed into a ratio of 3:1.

This approach is advantageous for handling sound levels, where the ratio of the highest to the lowest sound which we are likely to encounter is as high as 1,000,000 to 1. A useful development, many years ago, was to take the ratios with respect to the quietest sound which we can hear. This is the threshold of hearing at 1,000 Hz, which is 20 microPascals (μPa) ($2x10^{-5}$Pa) of pressure for the average young healthy person. Sound powers in decibels are taken with respect to a reference level of 10^{-12} watts.

When the word "level" is added to the word for a physical quantity, decibel levels are implied, denoted by L_X, where $_X$ is the symbol for the quantity.

$$\text{Pressure level} \quad L_p = 20\log_{10}\left[\frac{P}{P_0}\right] \text{ dB}$$

where P is the measured pressure and P_0 is the reference pressure level of $2x10^{-5}$ Pa

A little calculation allows us to express the sound pressure level at a distance from a source of known sound power level as

Sound pressure level, $L_P = L_w - 20\log[r] - 11$ dB

Where L_p is the sound pressure level
L_w is the sound power level of the source
r is the distance from the source

This is the basic equation for spherical sound propagation. It is used in prediction of wind turbine sound but, in a real calculation, has many additions to it, to take into account the atmospheric, ground and topographic conditions. However, as a simple calculation, the sound level at a distance of 500m from a source of sound power 100 dBA is 35 dBA.

Equivalent level (Leq): This is a steady level over a period of time, which has the same energy as that of the fluctuating level actually occurring during that time. A-weighted equivalent level, designated LAeq, is used for many legislative purposes, including for assessment of wind turbine sound.

Percentiles (LN)L These are a statistical measure of the fluctuations in overall noise level, that is, in the envelope of the noise, which is usually sampled a number of times per second, typically ten times. The most used percentiles are L90 and L10. The L90 is the level exceeded for 90 percent of the time and represents a low level in the noise. It is often used to assess

background noise. The L10 is the level exceeded for 10 percent of the time and is a measure of the higher levels in a noise. Modern computing sound level meters give a range of percentiles. Note that the percentile is a statistical measure over a specified time interval.

Frequency Analysis

This gives more detail of the frequency components of a noise. Frequency analysis normally uses one of three approaches: octave band, one-third octave band or narrow band.

Narrow band analysis is most useful for complex tonal noises. It could be used, for example, to determine a fan tone frequency, to find the frequencies of vibration transmission from machinery or to detect system resonances. All analyses require an averaging over time, so that the detail of fluctuations in the noise is normally lost.

Criteria for assessment of noise are based on dBA, octave bands, or 1/3-octave band measurements. These measures clearly give increasingly detailed information about the noise.

APPENDIX B

The Human Ear

APPENDIX B

The Human Ear

Humans have ears with three general regions:

1. An *outer ear*, including an ear (auditory) canal
2. An air-containing *middle ear* that includes an eardrum and small bones called ossicles (three in mammals, one in other animals)
3. An *inner ear* that includes organs of hearing (in mammals, this is the organ of Corti in the cochlea) and balance (vestibular labyrinth)

Airborne sound passes thorough the ear canal, making the eardrum and ossicles vibrate, and this vibration then sets the fluids of the cochlea into motion. Specialized "hair cells" convert this fluid movement into nerve impulses that travel to the brain along the auditory nerve. The hair cells, nerve cells, and other cells in the cochlea can be damaged by excessive noise, trauma, toxins, ear diseases, and as part of the aging process. Damage to the cochlea causes "sensorineural hearing loss," the most common type of hearing loss in the United States.

It is essential to understand the role of the middle ear, as well as the difference between air conduction and bone conduction. The middle ear performs the essential task of converting airborne sound into inner ear fluid movement, a process known as impedance matching (air is a low-impedance medium, meaning that its molecules move easily in response to sound pressure, while water is a high-impedance medium). Without impedance matching, over 99.9 percent of airborne sound energy is reflected away from the body. The middle ear enables animals living in air to hear very soft sounds that would otherwise be inaudible, but it is unnecessary for animals that live in water, because sound traveling in water passes easily into the body (which is mostly water). When a child has an ear infection, or an adult places earplugs in his ears, a "conductive hearing loss" dramatically reduces the transmission of airborne sound into the inner ear. People with conductive hearing loss can still hear sounds presented directly to the skull by "bone conduction." This is how both humans and fishes hear underwater or when a vibrating tuning fork is applied to the head, but it requires much more acoustic energy than air conduction hearing.

APPENDIX C

Measuring Sound

APPENDIX C

Measuring Sound

A sound level meter is the standard way of measuring sound. Environmental sound is normally assessed by the A-weighting. Although hand-held instruments appear to be easy to use, lack of understanding of their operation and limitations, and the meaning of the varied measurements which they can give, may result in misleading readings.

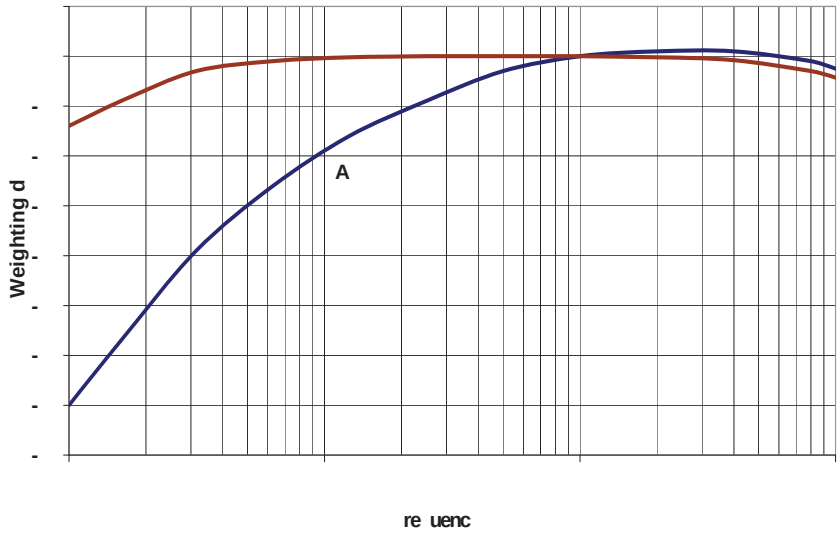
The weighting network and electrical filters are an important part of the sound level meter, as they give an indication of the frequency components of the sound. The filters are as follows:

- A-weighting: on all meters
- C-weighting: on most meters
- Linear (Z-weighting): on many meters
- Octave filters: on some meters
- Third octave filters: on some meters
- Narrow band: on a few meters

Sound level meter weighting networks are shown in Figure C-1. Originally, the A-weighting was intended for low levels of noise. C-weighting was intended for higher levels of noise. The weighting networks were based on human hearing contours at low and high levels and it was hoped that their use would mimic the response of the ear. This concept, which did not work out in practice, has now been abandoned and A- and C-weighting are used at all levels. Linear weighting is used to detect low frequencies. A specialist G-weighting is used for infrasound below 20 Hz.

Figure C-1 shows that the A-weighting depresses the levels of the low frequencies, as the ear is less sensitive to these. There is general consensus that A-weighting is appropriate for estimation of the hazard of NIHL. With respect to other effects, such as annoyance, A-weighting is acceptable if there is largely middle and high frequency noise present, but if the noise is unusually high at low frequencies, or contains prominent low frequency tones, the A-weighting may not give a valid measure. Compared with other noise sources, wind turbine spectra, as heard indoors at typical separation distances, have less low frequency content than most other sources (Pedersen, 2008).

FIGURE C-1
Weighting Networks



APPENDIX D
Propagation of Sound

APPENDIX D

Propagation of Sound

The propagation of noise from wind turbines is determined by a number of factors, including:

- Geometrical spreading, given by K = 20log[r] –11 dB, at a distance r
- Molecular absorption. This is conversion of acoustic energy to heat and is frequency dependent
- Turbulent scattering from local variations in wind velocity and air temperature and is moderately frequency dependent
- Ground effects—reflection, topography and absorption are frequency dependent; their effects increasing as the frequency increases
- Near surface effects—temperature and wind gradients.

The sound pressure at a point, distant from source, is given by

$$L_P = L_W - K - D - A_A - A_G \qquad \text{(dB)}$$

In which:

L_P is the sound pressure at the receiving point

L_W is the sound power of the turbine in decibels re 10^{-12} watts

K is the geometrical spreading term, which is inherent in all sources

D is a directivity index, which takes non-uniform spreading into account

A_A is an atmospheric absorption and other near surface effects term

A_G is a ground absorption and other surface effects term

Near surface meteorological effects are complex, as wind and temperature gradients affect propagation through the air.

APPENDIX E

Expert Panel Members

APPENDIX E

Expert Panel Members

Members of the expert panel are listed below. Biographies of each member are provided following the list.

Expert Panel Members

W. David Colby, M.D.

Chatham-Kent Medical Officer of Health (Acting)
Associate Professor, Schulich School of Medicine & Dentistry, University of Western Ontario

Robert Dobie, M.D.

Clinical Professor, University of Texas, San Antonio
Clinical Professor, University of California, Davis

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ar astasch

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Panel Member Biographies

W. David Colby, M.D.

W. David Colby M.Sc., M.D., FRCPC, is a fellow of the Royal College of Physicians and Surgeons of Canada in Medical Microbiology. Dr Colby is the Acting Medical Officer of Health in Chatham-Kent, Ontario and Associate Professor of Medicine, Microbiology/Immunology and Physiology/Pharmacology at the Schulich School of Medicine and Dentistry at the University of Western Ontario. He received his M.D. from the University of Toronto and completed his residency at University Hospital, London, Ontario. While still a resident he was given a faculty appointment and later was appointed Chief of Microbiology and Consultant in Infectious Diseases at University Hospital. Dr Colby lectures extensively on antimicrobial chemotherapy, resistance and fungal infections in addition to a busy clinical practice in Travel Medicine and is a Coroner for the province of Ontario. He has received numerous awards for his teaching. Dr. Colby has a number of articles in peer-reviewed journals and is the author of the textbook *Optimizing Antimicrobial Therapy: A Pharmacometric Approach.* He is a Past President of the Canadian Association of Medical Microbiologists. On the basis of his expertise in Public Health, Dr Colby was asked by his municipality to assess the health impacts of wind turbines. The report, titled *The Health Impact of Wind Turbines: A Review of the Current White,Grey, and Published Literature* is widely cited internationally.

Robert Dobie, M.D.

Robert Dobie, M.D., is clinical professor of otolaryngology at both the University of Texas Health Science Center at San Antonio and the University of California-Davis. He is also a partner in Dobie Associates, a consulting practice specializing in hearing and balance, hearing conservation, and ear disorders. The author of over 175 publications, his research interests include age-related and noise-induced hearing loss, as well as tinnitus and other inner ear disorders. He is past president of the Association for Research in Otolaryngology, past chair of the Hearing and Equilibrium Committee of the American Academy of Otolaryngology-Head and Neck Surgery, and has served on the boards and councils of many other professional organizations and scholarly journals.

Geoff Leventhall, Ph.D.

Geoff is a UK-based noise and vibration consultant who works internationally. His academic and professional qualifications include Ph.D. in Acoustics, Fellow of the UK Institute of Physics, Honorary Fellow of the UK institute of Acoustics (of which he is a former President), Distinguished International Member of the USA Institute of Noise Control Engineering, Member of the Acoustical Society of America.

He was formerly an academic, during which time he supervised 30 research students to completion of their doctoral studies in acoustics. Much of his academic and consultancy work has been on problems of infrasound and low frequency noise and control of low frequency noise by active attenuation

He has been a member of a number of National and International committees on noise and acoustics and was recently a member of two committees producing reports on effects of noise on health: the UK Health Protection Agency Committee on the Health Effects of

Ultrasound and Infrasound and the UK Department of Health Committee on the Effects of Environmental Noise on Health.

David M. Lipscomb, Ph.D.

Dr. David M. Lipscomb received a Ph. D. in Hearing Science from the University of Washington (Seattle) in 1966. Dr. Lipscomb taught at the University of Tennessee for more than two decades in the Department of Audiology and Speech Pathology. While he was on the faculty, Dr. Lipscomb developed and directed the department's Noise Research Laboratory. During his tenure at Tennessee and after he moved to the Pacific Northwest in 1988, Dr. Lipscomb has served as a consultant to many entities including communities, governmental agencies, industries, and legal organizations.

Dr. Lipscomb has qualified in courts of law as an expert in Audiology since 1966. Currently, he investigates incidents to determine whether an acoustical warning signal provided warning to individuals in harms way, and, if so, at how many seconds before an incident. With his background in clinical and research audiology, he undertakes the evaluation of hearing impairment claims for industrial settings and product liability.

Dr. Lipscomb was a bioacoustical consultant to the U. S. Environmental Protection Agency Office of Noise Abatement and Control (ONAC) at the time the agency was responding to Congressional mandates contained in the Noise Control Act of 1972. He was one of the original authors of the Criteria Document produced by ONAC, and he served as a reviewer for the ONAC document titled *Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety*. Dr. Lipscomb's experience in writing and reviewing bioacoustical documentation has been particularly useful in his review of materials for AWEA regarding wind farm noise concerns.

Robert J. McCunney, M.D.

Robert J. McCunney, M.D., M.P.H., M.S., is board certified by the American Board of Preventive Medicine as a specialist in occupational and environmental medicine. Dr. McCunney is a staff physician at Massachusetts General Hospital's pulmonary division, where he evaluates and treats occupational and environmental illnesses, including lung disorders ranging from asbestosis to asthma to mold related health concerns, among others. He is also a clinical faculty member of Harvard Medical School and a research scientist at the Massachusetts Institute of Technology Department of Biological Engineering, where he participates in epidemiological research pertaining to occupational and environmental health hazards.

Dr. McCunney received his B.S. in chemical engineering from Drexel University, his M.S. in environmental health from the University of Minnesota, his M.D. from the Thomas Jefferson University Medical School and his M.P.H. from the Harvard School of Public Health. He completed training in internal medicine at Northwestern University Medical Center in Chicago. Dr. McCunney is past president of the American College of Occupational and Environmental Medicine (ACOEM) and an accomplished author. He has edited numerous occupational and environmental medicine textbooks and over 80 published articles and book chapters. He is the Editor of all three editions of the text book, *A Practical Approach to Occupational and Environmental Medicine*, the most recent edition of which was published in 2003. Dr. McCunney received the Health Achievement Award from ACOEM in 2004.

Dr. McCunney has extensive experience in evaluating the effects of noise on hearing via reviewing audiometric tests. He has written book chapters on the topic and regularly lectures at the Harvard School of Public Health on "Noise and Health."

ichael Seilo h D

Dr. Michael T. Seilo received his Ph.D. in Audiology from Ohio University in 1970. He is currently a professor of audiology in the Department of Communication Sciences and Disorders at Western Washington University in Bellingham, Washington where he served as department chair for a total of more than twenty years. Dr. Seilo is clinically certified by the American Speech-Language-Hearing Association (ASHA) in both audiology and speech-language pathology and is a long-time member of ASHA, the American Academy of Audiology, and the Washington Speech and Hearing Association.

For many years Dr. Seilo has taught courses in hearing conservation at both the graduate and undergraduate level. His special interest areas include speech perception and the impact of noise on human hearing sensitivity including tinnitus.

Dr. Seilo has consulted with industries on the prevention of NIHL and he has collaborated with other professionals in the assessment of hearing-loss related claims pertaining to noise.

Bo Søndergaard, M.Sc. (Physics)

Bo Søndergaard has more than 20 years of experience in consultancy in environmental noise measurements, predictions and assessment. The last 15 years with an emphasis on wind turbine noise. Mr. Søndergaard is the convenor of the MT11 work group under IEC TC88 working with revision of the measurement standard for wind turbines IEC 61400-11. He has also worked as project manager for the following research projects: Low Frequency Noise from Large Wind Turbines for the Danish Energy Authority, Noise and Energy optimization of Wind Farms, and Noise from Wind Turbines in Wake for Energinet.dk.

Technical Advisor Biography

Mark Bastasch

Mr. Bastasch is a registered acoustical engineer with CH2M HILL. Mr. Bastasch assisted AWEA and CanWEA in the establishment of the panel and provided technical assistance to the panel throughout the review process. Mr. Bastasch's acoustical experience includes preliminary siting studies, regulatory development and assessments, ambient noise measurements, industrial measurements for model development and compliance purposes, mitigation analysis, and modeling of industrial and transportation noise. His wind turbine experience includes some of the first major wind developments including the Stateline project, which when built in 2001 was the largest in the world. He also serves on the organizing committee of the biannual International Wind Turbine Noise Conference, first held in Berlin, Germany, in 2005.

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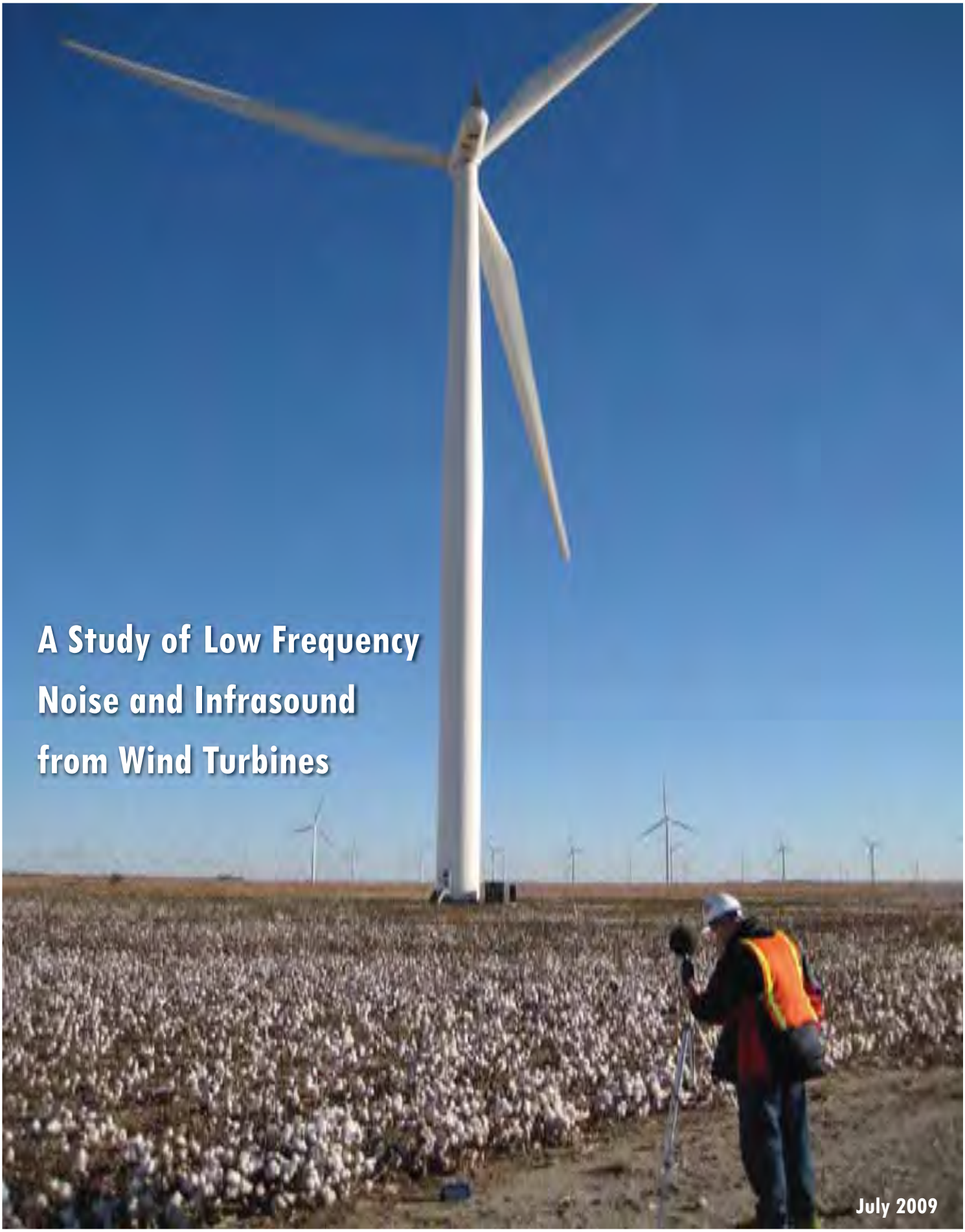

A Study of Low Frequency Noise and Infrasound from Wind Turbines

July 2009

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ES EXECUTIVE SUMMARY

Early down-wind wind turbines in the US created low frequency noise; however current up-wind wind turbines generate considerably less low frequency noise. The results of Epsilon Associates, Inc. (Epsilon) analysis and field testing indicate that there is no audible infrasound either outside or inside homes at the any of the measurement sites – the closest site was approximately 900 feet from a wind farm. Wind farms at distances beyond 1000 feet meet the ANSI standard for low frequency noise in bedrooms, classrooms, and hospitals, meet the ANSI standard for thresholds of annoyance from low frequency noise, and there should be no window rattles or perceptible vibration of light-weight walls or ceilings within homes. In homes there may be slightly audible low frequency noise (depending on other sources of low frequency noise); however, the levels are below criteria and recommendations for low frequency noise within homes. In accordance with the above findings and in conjunction with our extensive literature search of scientific papers and reports, there should be no adverse public health effects from infrasound or low frequency noise at distances greater than 1000 feet from the wind turbine types measured by Epsilon: GE 1.5sle and Siemens SWT 2.3-93.

Siemens SWT 2.3-93 Wind Turbine. Outdoor measurements of Siemens SWT 2.3-93 wind turbines under high output and relatively low ground wind speed (which minimized effects of wind noise) at 1000 feet indicate that infrasound is inaudible to the most sensitive people (more than 20 dB lower than median thresholds of hearing); that outdoor equivalent ANSI/ASA S12.2 perceptible vibration criteria are met; that the low frequency sounds are compatible with ANSI S12.9 Part 4 levels for minimal annoyance and beginning of rattles; that levels meet outdoor equivalent UK Department for Environment, Food and Rural Affairs (DEFRA) disturbance-based guidelines for use by Environmental Health Officers, and that low frequency sounds might be audible in some cases. Based on the comparisons made to these criteria, there are no low frequency noise problems from Siemens SWT 2.3-93 wind turbines at 1000 feet or beyond.

Indoor measurements of two homes with windows open and closed of Siemens SWT 2.3-93 wind turbines at approximately 920 feet (under high output, maximum noise, and high ground winds) and at 1060 feet (under moderate-high output, maximum noise and relatively low ground winds) indicate infrasound is inaudible to the most sensitive people (more than 25 dB lower than median thresholds of hearing). The low frequency noise at 50 Hz and above might be slightly audible depending on background noises within the home or other external noises. The ANSI/ASA S12.2 low frequency criteria for bedrooms, classrooms and hospitals were met, as were the criteria for moderately perceptible vibrations in light-weight walls and ceilings. DEFRA disturbance based guidelines were met for steady low frequency sounds and were within 2 dB for non-steady low frequency sounds. Based on the comparisons made to these criteria, there are no low frequency noise problems indoors from Siemens SWT 2.3-93 wind turbines at 920 feet or beyond.

GE 1.5sle Wind Turbine. Outdoor measurements of GE 1.5sle wind turbines under high output and relatively low ground wind speed (which minimized effects of wind noise) at 1000 feet indicate that infrasound is inaudible to the most sensitive people (more than 20 dB lower than median thresholds of hearing); that outdoor equivalent ANSI/ASA S12.2 perceptible vibration criteria are

met; that the low frequency sounds are compatible with ANSI S12.9 Part 4 levels for minimal annoyance and beginning of rattles; that levels meet or are within 1 dB of outdoor equivalent DEFRA disturbance-based guidelines; and that the low frequency sounds might be audible in some cases. Based on the comparisons made to these criteria, there are no low frequency noise problems from GE 1.5sle wind turbines at 1000 feet or beyond.

Indoor measurements with windows open and closed of GE 1.5sle wind turbines at approximately 950 feet (under moderate output, maximum noise, and high ground winds) and at approximately 1025 feet (under moderate output, within 1.5 dBA of maximum noise, and high ground winds) indicate infrasound is inaudible to the most sensitive people (more than 25 dB lower than median thresholds of hearing). The low frequency noise at or above 50 or 63 Hz might be slightly audible depending on background noises within the home or other external noises. The ANSI/ASA S12.2 low frequency criteria for bedrooms, classrooms and hospitals were met, as were the criteria for moderately perceptible vibrations in light-weight walls and ceilings. DEFRA disturbance based guidelines were met for steady low frequency sounds and non-steady low frequency sounds. Based on the comparisons made to these criteria, there are no low frequency noise problems indoors for GE 1.5sle wind turbines at distances beyond 950 feet.

Conclusions. Siemens SWT 2.93-93 and GE 1.5sle wind turbines at maximum noise at a distance more than 1000 feet from the nearest residence do not pose a low frequency noise problem. At this distance the wind farms:

- meet ANSI/ASA S12.2 indoor levels for low frequency sound for bedrooms, classrooms and hospitals;
- meet ANSI/ASA S12.2 indoor levels for moderately perceptible vibrations in light-weight walls and ceilings;
- meet ANSI S12.9 Part 4 thresholds for annoyance and beginning of rattles;
- meet UK DEFRA disturbance based guidelines;
- have no audible infrasound to the most sensitive listeners;
- might have slightly audible low frequency noise at frequencies at 50 Hz and above depending on other sources of low frequency noises in homes, such as refrigerators or external traffic or airplanes; and
- meet ANSI S2.71 recommendations for perceptible ground-borne vibration in residences during night time hours.

1.0 INTRODUCTION

Epsilon Associates, Inc. ("Epsilon") has been retained by NextEra Energy Resources, LLC ("NextEra"), formerly FPL Energy, to investigate whether the operation of their wind turbines may create unacceptable levels of low frequency noise and infrasound. This question has been posed to NextEra, and other wind energy developers and operators of utility-scale wind turbines. NextEra is one of the world's largest generators of wind power with approximately 6,400 net megawatts (MW) as of April 2009.

Epsilon determined all means, methods, and the testing protocol without interference or direction from NextEra. No limitations were placed on Epsilon by NextEra with respect to the testing protocol or upon the analysis methods.

This report is composed of two distinct sections: the first portion defines terms, discusses known effects of low frequency sound, and presents scientific guidelines and standards used to evaluate low frequency sound. The second portion of the report examines specific wind turbines used by NextEra, including data from field measurements at operating wind farms, and compares the measured data to guidelines and standards. In addition, each NextEra wind turbine vendor supplied detailed, reference sound level data in both A-weighted and octave band format in accordance with the international standard IEC 61400-11, "Wind Turbine Generator Systems-Part 11; Acoustic Noise Measurement Techniques." These data were used as an aide to focus the field portion of the measurement program.

2.0 DEFINITIONS

2.1 Low Frequency Noise/Sound

The frequency range 20 – 20,000 Hz is commonly described as the range of *"audible"* noise. The frequency range of low frequency sound is generally from 20 Hertz (Hz) to 200 Hz, and the range below 20 Hz is often described as "*infrasound*". However, audibility extends to frequencies below 20 Hz.

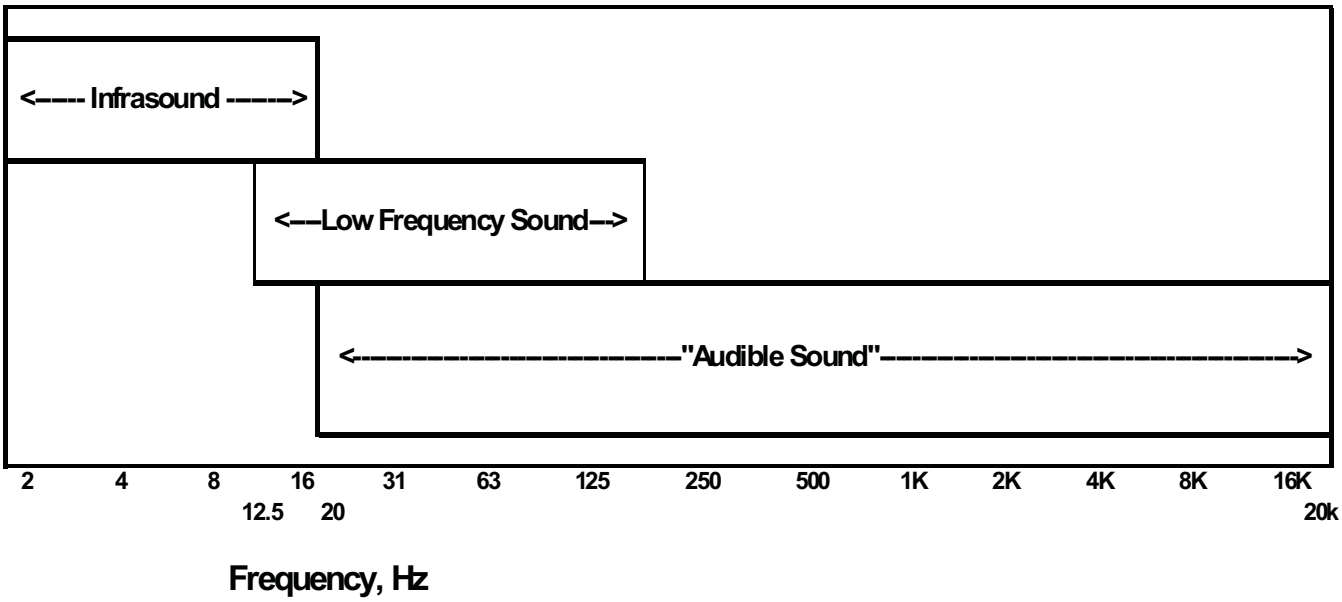
Low frequency sound has several definitions. American National Standards ANSI/ASA S12.2 and ANSI S12.9 Part 4 have provisions for evaluating low frequency noise, and these special treatments apply only to sounds in the octave bands with 16, 31.5, and 63-Hz mid-band frequencies. For these reasons, in this paper on wind turbine noise, we use the term "low frequency noise" to include 12.5 Hz – 200 Hz with emphasis on the 16 Hz, 31Hz and 63 Hz octave bands with a frequency range of 11 Hz to 89 Hz.

2.2 Infrasound

IEC 60050-801:1994 "International Electrotechnical Vocabulary – Chapter 801: Acoustics and electroacoustics" defines "*infrasound*" as "Acoustic oscillations whose frequency is below the low frequency limit of audible sound (about 16 Hz)." This definition is *incorrect* since sound remains audible at frequencies well below 16 Hz provided that the sound level is sufficiently high. In this paper we define infrasound to be below 20 Hz, which is the limit for the standardized threshold of hearing.

Figure 2.2-1 shows these frequency regions and their common labels. Since there is no sharp change in hearing at 20 Hz, the division into "low-frequency sound" and "infrasound" should only be considered "practical and conventional."

Figure 2.2-1 Frequency Range of "Infrasound", "Low Frequency Sound", and "Audible Sound".



3.0 EFFECTS OF LOW FREQUENCY SOUND AND INFRASOUND

3.1 Humans

3.1.1 Threshold of hearing

Moeller and Pedersen (2004) present an excellent summary on human perception of sound at frequencies below 200 Hz. The ear is the primary organ for sensing infrasound. Hearing becomes gradually less sensitive for decreasing frequencies. But, humans with a normal hearing organ can perceive infrasound at least down to a few hertz if the sound level is sufficiently high.

The threshold of hearing is standardized for frequencies down to 20 Hz (ISO 226:2003). Based on extensive research and data, Moeller and Pedersen propose normal hearing thresholds for frequencies below 20 Hz (see Figure 3.1-1). Moeller and Pedersen suggest that the curve for normal hearing is "probably correct within a few decibels, at least in most of the frequency range."

The hearing thresholds show considerable variability from individual to individual with a standard deviation among subjects of about 5 dB independent of frequency between 3 Hz and 1000 Hz with a slight increase at 20 – 50 Hz. This implies that the audibility threshold for 97.5% of the population is greater than the values in Figure 3.1-1 minus 10 dB and for 84% of the population is greater than the values in Figure 3.1-1 minus 5 dB. Moeller and Pedersen suggest using the pure-tone thresholds in Figure 3.1-1 for non-sinusoidal sound; this relationship is what is used in ISO 226 (International Organization for Standardization) for frequencies down to 20 Hz.

Below 20 Hz as frequency decreases, if the noise source is tonal, the tonal sensation ceases. Below 20 Hz tones are perceived as discontinuous. Below 10 Hz it is possible to perceive the single cycles of a tone, and the perception changes into a sensation of pressure at the ears.

3.1.2 Loudness

Below 100 Hz, the dynamic range of the auditory system decreases with decreasing frequency, and the compressed dynamic range has an effect on equal loudness contours: a slight change in sound level can change the perceived loudness from barely audible to loud. This combined with the large variation in individual hearing may mean that a low frequency sound that is inaudible to some may be audible to others, and may be relatively loud to some of those for whom it is audible. Loudness for low frequency sounds grows considerably faster above threshold than for sounds at higher frequencies. (Moeller and Pedersen, 2004)

3.1.3 Non-auditory perceptions

Non-auditory perception of low frequency and infrasound occurs only at levels above the auditory threshold. In the frequency range of 4 – 25 Hz and at "*levels 20 - 25 dB above [auditory] threshold it is possible to feel vibrations* in various parts of the body, e.g., the lumbar, buttock, thigh and calf regions. A feeling of pressure may occur in the upper part of the chest and the throat region" [emphasis added]. (Moeller and Pedersen, 2004).

3.2 Residential Structures

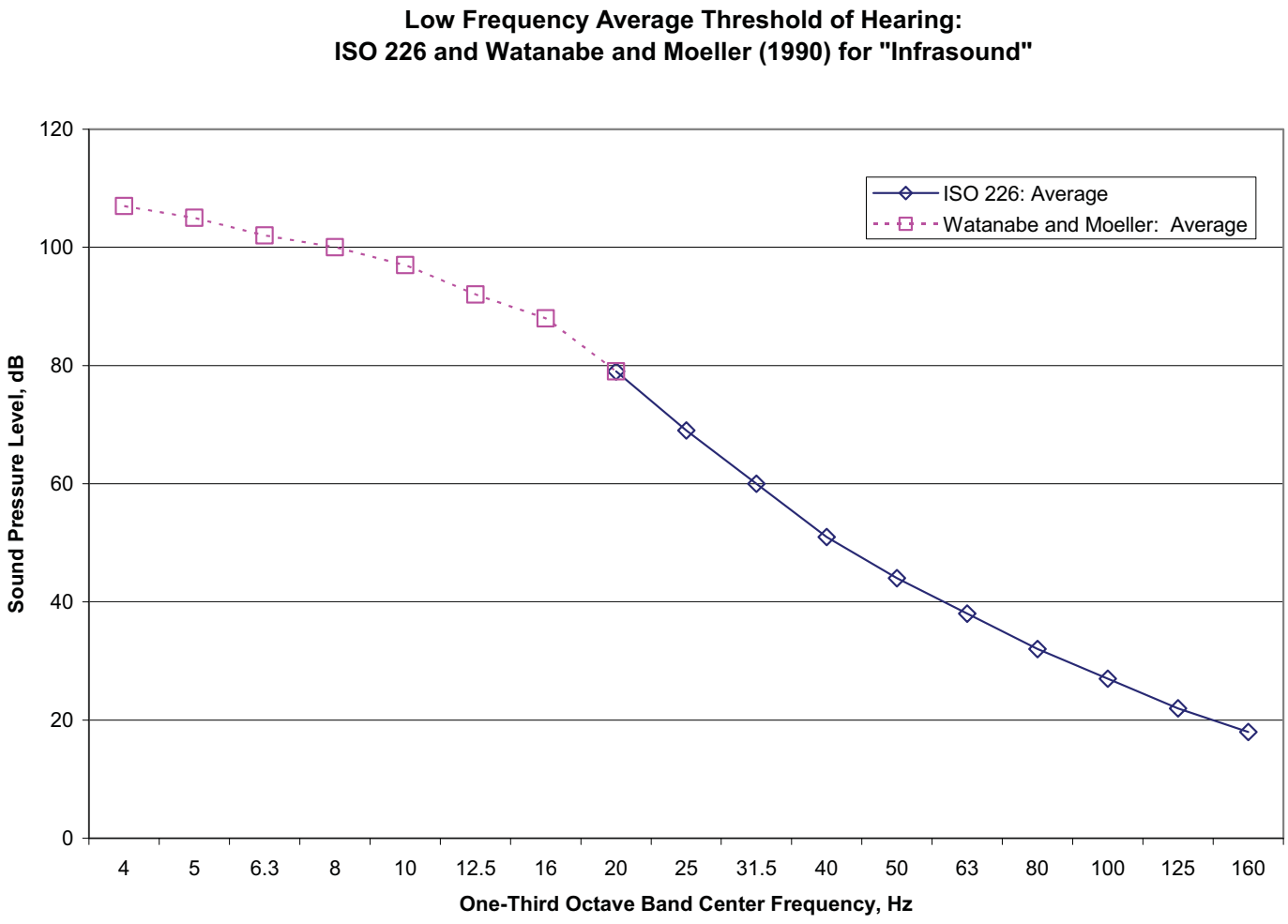
3.2.1 Airborne Vibration

Outdoor low frequency sounds of sufficient amplitude can cause building walls to vibrate and windows to rattle. Homes have low values of transmission loss at low frequencies, and low frequency noise of sufficient amplitude may be audible within homes. Window rattles are not low frequency noise, but may be caused by low frequency noise.

3.2.2 Ground borne Vibration

While not studied nearly as extensively as noise, a few papers were found that examined ground borne vibration from wind turbines (Styles, P. et al, 2005; Hayes McKenzie Partnership, 2006; Gastmeier and Howe (2008)). Measurement of ground borne vibration associated with wind turbine operations were detectable with instruments but were below the threshold of perception, even within the wind farm (Gastmeier and Howe 2008; Snow, D.J., 1997).

Figure 3.1-1 Low Frequency Average Threshold of Hearing



4.0 GUIDELINES AND CRITERIA

4.1 United States Government

There are no specific criteria for low frequency noise in the United States. The US Environmental Protection Agency (EPA) has guidelines for the protection of public health with an adequate margin of safety in terms of annual average A-weighted day-night average sound level (L_{dn}), but there are no corrections or adjustments for low frequency noise. The US Department of Transportation (DOT) has A-weighted sound pressure level criteria for highway projects and airports, but these do not have adjustments for low frequency noise.

4.2 American National Standards (voluntary)

4.2.1 ANSI/ASA S12.9-2007/Part 5

ANSI/ASA S12.9-2007/Part 5 "Quantities and Procedures for description and measurement of environmental sound. Part 5: Sound Level Descriptors for Determination of Compatible Land Use" has an informative annex which provides guidance for designation of land uses compatible with existing or predicted sound levels. The noise metric in ANSI S12.9 Part 5 is the annual average of the adjusted day-night average outdoor sound level (DNL). Ranges of the DNL are outlined, within which a specific region of compatibility may be drawn. These ranges take into consideration the transmission loss in sound level from outside to inside buildings as commonly constructed in that locality and living habits there. There are adjustments to day-night average sound level to account for the presence of low frequency noise, and the adjustments are described in ANSI S12.9 Part 4.

4.2.2 ANSI S12.9-2005/Part 4

ANSI S12.9-2005 Part 4 "Quantities and Procedures for description and measurement of environmental sound. Part 4: Noise assessment and prediction of long-term community response" provides procedures for assessing outdoor environmental sounds and provides for *adjustments* to measured or predicted adjusted annual outdoor day-night A-weighted sound level to account "for the change in annoyance caused by … sounds with strong low-frequency content…"

ANSI S12.9 Part 4 does not specifically define the frequency range for "low-frequency" sounds; however, evaluation methods for low frequency noise in Annex D use a sum of the sound pressure levels in the 16, 31 and 63 Hz octave bands. Procedures apply only when the difference in exterior C-weighted and A-weighted sound levels is greater than 10 dB, $(L_{pC} - L_{pA}) > 10$ dB. Complicated procedures are given for adjustments to L_{Aeq} and L_{dn} values. Adjustments are significant for high levels of low frequency sound.

ANSI S12.9 Part 4 states: "Generally, annoyance is minimal when octave-band sound pressure levels are less than 65 dB at 16, 31.5, and 63-Hz mid-band frequencies. However, low-frequency sound characterized by rapidly fluctuating amplitude … may cause annoyance when these octave-band sound pressure levels are less than 65 dB."

For sounds with strong low-frequency content, adjusted sound exposure level (LNE) is calculated from low-frequency sound pressure level L_{LF} by:

$$LNE = 2(L_{LF} - 65) + 55 + 10\log(t/1)$$

$$= 2\,L_{LF} - 75 + 10\log(t/1) \qquad \text{(Equation D.1 of ANSI S12.9 Part 4)}$$

where L_{LF} is 10 times the logarithm of the ratio of time-mean square sound pressures in the 16, 31.5, and 63-Hz octave bands divided by the square of the reference sound pressure and

t is the time duration of interest, in seconds, over which the low-frequency sound is present.

The factor of 2 in equation (D.1) accounts for the rapid increase in annoyance with sound pressure level at low frequencies. ANSI S12.9 Part 4 states: "Equation (D.1) also accounts for the additional annoyance from rattles that begins when the low-frequency sound pressure level [L_{LF}] exceeds 75 dB." Later, ANSI S12.9/Part 4 has a contradictory recommendation: "To prevent the likelihood of noise-induced rattles, the low-frequency sound pressure level [L_{LF}] should be less than 70 dB."

ANSI S12.9 /Part 4 identifies two thresholds: annoyance is minimal when the 16, 31.5 and 63 Hz octave band sound pressure levels are each less than 65 dB and there are no rapidly fluctuations of the low frequency sounds. The second threshold is for increased annoyance which begins when rattles occur, which begins at L_{LF} 70 - 75 dB. Since determination of L_{LF} involves integrating concurrently the sound pressures in the three octave bands, an energy sum of the levels in each of these separate bands results in an upper bound to L_{LF}. (The sound pressure level from the summation of these bands will always be less than L_{LF} since the sound pressures are not in phase within these three bands.)

It should be noted that a recent study on low frequency noise from aircraft operations (Hodgdon, Atchley, Bernhard 2007) reported that an expert panel was critical of using this L_{LF} metric because it had not previously been used to characterize aircraft noise and its reliance on the 16 Hz band since aircraft data does not extend down to 16 Hz and can not be used with the FAA Integrated Noise Model.

The adjustment procedure for low frequency noise to the average annual A-weighted sound pressure level in ANSI S12.9 Part 4 uses a different and more complicated metric and procedure (Equation D.1) than those used for evaluating low frequency noise in rooms contained in ANSI/ASA S12.2. (See section 4.2.3). Since we are evaluating low frequency

noise and not A-weighted levels, we do not recommend using the procedure for adjusting A-weighted levels. Instead we recommend using the following two guidelines from ANSI S12.4 Part 9: a sound pressure level of 65 dB in each of the 16-, 31.5-, and 63 Hz octave bands as an indicator of minimal annoyance, and 70 - 75 dB for the summation of the sound pressure levels from these three bands as an indicator of possible increased annoyance from rattles. This method is conservative since the sum of the levels in the three bands will always be less than L_{LF}.

4.2.3 ANSI/ASA S12.2-2008

ANSI/ASA S12.2-2008 discusses criteria for evaluating room noise, and has two separate provisions for evaluating low frequency noise: (1) the potential to cause perceptible vibration and rattles, and (2) meeting low frequency portions of room criteria curves.

Vibration and Rattles: Clause 6 and Table 6 of this standard contain limiting values of sound pressure levels for vibrations and rattles from low frequency noise. The frequency range is not defined, but limiting values and discussion relate only to octave-bands with center frequencies of 16, 31 and 63 Hz. This is the same narrow frequency range from low-frequency sounds as in ANSI S12.9/Part 4. Therefore, ANSI S12.9 Part 4 and ANSI/ASA S12.2 are consistent in evaluating and assessing low frequency sounds both for annoyance (interior and exterior measurements) and vibration (interior measurements) by using sound pressure levels only in the 16, 31 and 63 Hz octave-bands.

ANSI/ASA S12.2 presents limiting levels at low frequencies for assessing (a) the probability of *clearly* perceptible acoustically induced vibration and rattles in lightweight wall and ceiling constructions, and (b) the probability of *moderately* perceptible acoustically induced vibration in similar constructions. These 16, 31.5 and 63 Hz octave band sound pressure level values are presented in Table 4.2-1. One set of values is for when "clearly perceptible vibration and rattles" is likely, and a lower set of values is for when "moderately perceptible vibration and rattles" is likely.

Table 4.2-1 Measured interior sound pressure levels for perceptible vibration and rattle in lightweight wall and ceiling structures. [ANSI/ASA S12.2-2008]

Condition	Octave-band center frequency (Hz)		
	16	31.5	63
Clearly perceptible vibration and rattles likely	75 dB	75 dB	80 dB
Moderately perceptible vibration and rattles likely	65 dB	65 dB	70 dB

Since indoor measurements are not always possible, for comparison to outdoor sound levels the indoor criteria from ANSI/ASA S12.2 should be adjusted. Outdoor to indoor low frequency noise reductions have been reported by Sutherland for aircraft and highway noise

for open and closed windows (Sutherland 1978) and by Hubbard for aircraft and wind turbine noise for closed windows (Hubbard 1991). Table 4.2-2 presents the average low frequency octave band noise reductions from outdoor to indoors from these two papers for open and closed windows. Sutherland only reported values down to 63 Hz; whereas Hubbard presented values to less than 10 Hz. The closed window conditions of Hubbard were used to estimate noise reductions less than 63 Hz by applying the difference between values for open and closed windows from Sutherland data at 63 Hz. It should be noted that the attenuation for wind turbines in Hubbard is based on only three homes at two different wind farms, whereas the traffic and aircraft data are for many homes. The wind turbine open window values were obtained from the wind turbine closed window values by subtracting the difference in values between windows closed and open obtained by Sutherland.

Table 4.2-2 Average low frequency octave band noise reductions from outdoor to indoors in dB (based on Sutherland (1978) and Hubbard (1991))

Noise Source	Window condition	Octave Band Center Frequency		
		16 Hz	31.5 Hz	63 Hz
Average aircraft and traffic sources	Closed windows	16	15	18
Average aircraft and traffic sources	Open Windows	(11)*	(10)*	12
Average Wind Turbine	Closed Windows	8	11	14
Average Wind Turbine	**Open Windows**	**(3)*+**	**(6)* +**	**9+**

* No data are available for windows open below 63 Hz octave band. The values for 16 Hz and 31 Hz were obtained by subtracting the difference between the levels for 63 Hz closed and open conditions to the 16 and 31 Hz closed values.

\+ Used in this report to determine equivalent outdoor criteria from indoor criteria

To be conservative, we use the open window case instead of closed windows. To be further conservative, we use the wind turbine data (adjusted to open windows), which is based on only three homes. However, it should be noted that it is possible for some homes to have some slight amplification at low frequencies with windows open due to possible room resonances. Applying the outdoor to indoor attenuations for wind turbine sources with windows open given in the last row of Table 4.2-2 to the ANSI/ASA S12.2 indoor sound pressure levels in Table 4.2-1 yields the *equivalent* outdoor sound pressure levels that are consistent with the indoor criteria and are presented in Table 4.2-3.

Table 4.2-3 *Equivalent* outdoor sound pressure levels for perceptible vibration and rattle in lightweight wall and ceiling structures based on Tables 4.2-1 and 4.2-2 above for wind turbines.

Condition	Octave-band center frequency (Hz)		
	16	31.5	63
Clearly perceptible vibration and rattles likely	78 dB	81 dB	89 dB
Moderately perceptible vibration and rattles likely	68 dB	71 dB	79 dB

Room Criteria Curves: ANSI/ASA S12.2 has three primary methods for evaluating the suitability of noise within rooms: a survey method - A-weighted sound levels, an engineering method – noise criteria (NC) curves and a method for evaluating low-frequency fluctuating noise using room noise criteria (RNC) curves. "The RNC method should be used to determine noise ratings when the noise from HVAC systems at low frequencies is *loud* and is suspected of containing *sizeable fluctuations or surging*." [emphasis added] The NC curves are appropriate to evaluate low frequency noise from wind turbines in homes since wind turbine noise does not have significant fluctuating low frequency noise sufficient to warrant using RNC curves and since A-weighted sound levels do not adequately determine if there are low frequency problems. [ANSI/ASA S12.2. section 5.3 gives procedures for determining if there are large fluctuations of low frequency noise.]

Annex C.2 of this standard contains recommendations for bedrooms, which are the most stringent rooms in homes: NC and RNC criteria curve between 25 and 30. The recommended NC and RNC criteria for schools and private rooms in hospitals are the same. The values of the sound pressure levels in the 16 – 250 Hz octave bands for NC curves 25 and 30 are shown in Table 4.2-4.

Table 4.2-4 Octave band sound pressure levels for noise criteria curves NC-25 and NC-30. [From Table 1 of ANSI/ASA S12.2]

	Octave-band-center frequency in Hz				
	16	31.5	63	125	250
NC-25	80	65	54	44	37
NC-30	81	68	57	48	41

ANSI/ASA S12.2 also presents a method to determine if the levels below 500 Hz octave band are too high in relation to the levels in the mid-frequencies which could create a condition of "spectrum imbalance". The method for this evaluation is:

- Calculate the speech interference level (SIL) for the measured spectrum. [SIL is the arithmetic average of the sound pressure levels in the 500, 1000, 2000 and 4000 Hz octave bands.] Select the NC curve equal to the SIL value.

- Plot the measured spectra and the NC curve equal to the SIL value on the same graph and determine the differences between the two curves in the octave bands below 500 Hz.

- Estimate the likelihood that the excess low-frequency levels will annoy occupants of the space using Table 4.2-5.

Table 4.2-5 Measured sound pressure level deviations from an NC (SIL) curve that may lead to serious complaints [From ANSI/ASA S12.2:2008].

	Measured Spectrum – NC(SIL), dB			
Octave-band frequency, Hz = >	31.5	63	125	250
Possible serious dissatisfaction	*	6 - 9	6 - 9	6 - 9
Likely serious dissatisfaction	*	>9	>9	>9

*Insufficient data available to evaluate

4.3 Other Criteria

4.3.1 World Health Organization (WHO)

No specific low frequency noise criteria are proposed by the WHO. The Guidelines for Community Noise report (WHO, 1999) mentions that if the difference between dBC and dBA is greater than 10 decibels, then a frequency analysis should be performed to determine if there is a low frequency issue. A document prepared for the World Health Organization states that "there is no reliable evidence that infrasounds below the hearing threshold produce physiological or psychological effects. Infrasounds slightly above detection threshold may cause perceptual effects but these are of the same character as for 'normal' sounds. Reactions caused by extremely intense levels of infrasound can resemble those of mild stress reaction and may include bizarre auditory sensations, describable as pulsation and flutter" [Berglund (1995) p. 41]

4.3.2 The UK Department for Environment, Food, and Rural Affairs (DEFRA)

The report prepared by the University of Salford for the UK Department for Environment, Food, and Rural Affairs (DEFRA) on low frequency noise proposed one-third octave band sound pressure level L_{eq} criteria and procedures for assessing low frequency noise [DEFRA (2005)]. The guidelines are based on complaints of disturbance from low frequency sounds and are intended to be used by Environmental Health Officers. Reports by Hayes (2006) and others refer to the proposed criteria as "DEFRA criteria." Tables 4.3-1 and 4.3-2 present

the DEFRA criteria for assessment of low frequency noise measured indoors. The criteria are "based on 5 dB below the ISO 226 (2003) average threshold of audibility for steady [low frequency] sounds." However, the DEFRA criteria are at 5 dB lower than ISO 226 only at 20 - 31.5 Hz; at higher frequencies the criteria are equal to the Swedish criteria which are higher levels than ISO 226 less 5 dB. For frequencies lower than 20 Hz, DEFRA uses the thresholds from Watanabe and Moeller (1990) less 5 dB. In developing the DEFRA guidelines, The University of Salford reviewed and considered existing low frequency noise criteria from several European countries.

The DEFRA criteria are based on measurements in an unoccupied room. Hayes Mackenzie (2006) noted that measurements should be made with windows closed; however, we conservatively used windows open conditions for our assessment. If the low frequency sound is "steady" then the criteria may be relaxed by 5 dB. A low frequency noise is considered steady if either of the conditions a) or b) below is met in the third octave band which exceeds the criteria by the greatest margin:

a) L_{10}-L_{90} < 5dB

b) the rate of change of sound pressure level (Fast time weighting) is less than 10 dB per second

Applying indoor to outdoor one-third octave band transfer functions for open windows (from analysis in Sutherland (1978) and Hubbard (1991) yields *equivalent* one-third octave band sound pressure level proposed DEFRA criteria for outdoor sound levels. Table 4.3-1 presents both the indoor DEFRA proposed criteria and equivalent proposed criteria for outdoors for non-steady low-frequency sounds. Table 4.3-2 presents the DEFRA proposed criteria for a steady low frequency sound.

Table 4.3-1 DEFRA proposed criteria for the assessment of low frequency noise disturbance: *indoor* and *equivalent outdoor* L_{eq} one-third sound pressure levels for *non-steady* low frequency sounds. [DEFRA (2005)]

Location	One-Third Octave Band Center Frequency, Hz												
	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160
Indoor L_{eq}, dB	92	87	83	74	64	56	49	43	42	40	38	36	34
Equivalent Outdoor L_{eq}, dB	94	89	86	78	68.5	61	56	51	51	49	47	45	43

Table 4.3-2 DEFRA criteria for the assessment of low frequency noise disturbance: *indoor* and *equivalent outdoor* L_{eq} one-third sound pressure levels for *steady* low frequency sounds. [DEFRA (2005)]

Location	One-Third Octave Band Center Frequency, Hz												
	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160
Indoor L_{eq}, dB	97	92	88	79	69	61	54	48	47	45	43	41	39
Equivalent Outdoor* L_{eq}, dB	99	94	91	83	73.5	66	61	56	56	54	52	50	48

* With windows open

4.3.3 C-weighted minus A-weighted (L_{pC}- L_{pA})

Leventhall (2003) and others indicate that the difference in C-weighted and A-weighted sound pressure levels can be a predictor of annoyance. Leventhall states that if (L_{pC} – L_{pA}) is greater than 20 dB there is "a potential for a low frequency noise problem." He further states that (L_{pC} – L_{pA}) cannot be a predictor of annoyance but is a simple indicator that further analysis may be needed. This is due in part to the fact that the low frequency noise may be inaudible even if (L_{pC} – L_{pA}) is greater than 20 dB.

4.3.4 Threshold of hearing

ISO 226:2003 gives one-third octave band threshold of hearing down to 20 Hz. Watanabe and Moeller (1990) have extended these to 10 Hz and lower, and the values are reported in Moeller and Pedersen (2004). Denmark has established low frequency noise criteria based on audibility. The Danish criteria are "based on hearing thresholds for the 10% most sensitive people in an ontologically unselected population aged 50-60 years. These 10% thresholds are typically about 4-5 dB lower than the average threshold for ontologically normal young adults (18-25 years) as given in ISO 226." [DEFRA (2005)]. Other reports indicate that the standard deviation of these thresholds is also about 5 dB. Table 4.3-3 presents one-third octave band threshold of hearing according to ISO 226 and Watanabe and Moeller. The second row in Table 4.3-3 presents the values that are 5 dB less than the threshold.

Table 4.3-3 Threshold of audibility from ISO 226 and Watanabe and Moeller (1990)

	One-Third Octave band center frequency, Hz																
	4	5	6.3	8	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160
Threshold	107	105	102	100	97	92	88	79	69	60	51	44	38	32	27	22	18
Threshold – 5 dB	102	100	97	95	92	87	83	74	64	55	46	39	33	27	22	17	13

The average threshold of hearing values in Table 4.3-3 are also shown in Figure 3.1-1.

4.3.5 Ground-Borne Vibration

ANSI S2.71-1983 (formerly ANSI S3.29-1983) presents recommendations for magnitudes of ground-borne vibration which humans will perceive and possibly react to within buildings. A basic rating is given for the most stringent conditions, which correspond to the approximate threshold of perception of the most sensitive humans. From the base rating, multiplication factors should be applied according to the location of the receiver; for continuous sources of vibration in residences at nighttime, the multiplication factor is 1.0 – 1.4.

ANSI S2.71-1983 presents one-third octave band acceleration or velocity ratings for z-axis, and x-, y-axis vibrations. For spaces in which the occupants may be sitting, standing, or lying at various times, the standard recommends using a combined axis rating which is obtained from the most stringent rating for each axis. Measurements in each of the 3 axes should be compared to the combined axis rating. Table 4.3-4 presents the base response velocity ratings for the combined axis. The velocity ratings are for root-mean-square (RMS) values.

Table 4.3-4 Base response one-third octave band RMS velocity ratings for the three biodynamic vibration axes and combined axis (From ANSI S2.71-1983 (R2006)

One-Third Octave band center frequency, Hz	Velocity (RMS), m/s		
	z axis	x, y axis	Combined axis
1	1.6×10^{-3}	5.7×10^{-4}	5.7×10^{-4}
1.25	1.1×10^{-3}	4.6×10^{-4}	4.6×10^{-4}
1.6	8.0×10^{-4}	3.6×10^{-4}	3.6×10^{-4}
2	5.6×10^{-4}	2.9×10^{-4}	2.9×10^{-4}
2.5	4.0×10^{-4}	2.9×10^{-4}	2.4×10^{-4}
3.15	2.9×10^{-4}	2.9×10^{-4}	2.1×10^{-4}
4	2.0×10^{-4}	2.9×10^{-4}	1.7×10^{-4}
5	1.6×10^{-4}	2.9×10^{-4}	1.4×10^{-4}
6.3	1.3×10^{-4}	2.9×10^{-4}	1.2×10^{-4}
8	1.0×10^{-4}	2.9×10^{-4}	1.0×10^{-4}
10	1.0×10^{-4}	2.9×10^{-4}	1.0×10^{-4}
12.5	1.0×10^{-4}	2.9×10^{-4}	1.0×10^{-4}
16	1.0×10^{-4}	2.9×10^{-4}	1.0×10^{-4}
20	1.0×10^{-4}	2.9×10^{-4}	1.0×10^{-4}
25	1.0×10^{-4}	2.9×10^{-4}	1.0×10^{-4}
31.5	1.0×10^{-4}	2.9×10^{-4}	1.0×10^{-4}
40	1.0×10^{-4}	2.9×10^{-4}	1.0×10^{-4}
50	1.0×10^{-4}	2.9×10^{-4}	1.0×10^{-4}
63	1.0×10^{-4}	2.9×10^{-4}	1.0×10^{-4}
80	1.0×10^{-4}	2.9×10^{-4}	1.0×10^{-4}

5.0 LITERATURE REVIEW

Epsilon performed an extensive literature search of over 100 scientific papers, technical reports and summary reports on low frequency sound and infrasound - hearing, effects, measurement, and criteria. The following paragraphs briefly summarize the findings from some of these papers and reports.

5.1 H. Moeller and C. S. Pedersen (2004)

Moeller and Pedersen (2004) present a comprehensive summary on hearing and non-auditory perception of sound at low and infrasonic regions, some of which has been cited in sections 3.1.1, 3.1.2, and 3.1.3 of this report.

5.2 Leventhall (2003)

Leventhall presents an excellent study on low frequency noise from all sources and its effects. The report presents criteria in place at that time. Included are figures and data relating cause and effects.

5.3 Leventhall (2006)

Leventhall reviewed data and allegations on alleged problems from low frequency noise and infrasound from wind turbines. Leventhall concluded the following: "It has been shown that there is insignificant infrasound from wind turbines and that there is normally little low frequency noise." "Turbulent air inflow conditions cause enhanced levels of low frequency noise, which may be disturbing, but the overriding noise from wind turbines is the fluctuating audible swish, mistakenly referred to as "infrasound" or "low frequency noise". "Infrasound from wind turbines is below the audible threshold and of no consequence". Other studies have shown that wind turbine generated infrasound levels are below threshold of perception and threshold of feeling and body reaction.

5.4 Delta (2008)

The Danish Energy Authority project on "low frequency noise from large wind turbines" comprises a series of investigations in the effort to give increased knowledge on low frequency noise from wind turbines. One of the conclusions of the study is that wind turbines do not emit audible infrasound, with levels that are "far below the hearing threshold." Audible low frequency sound may occur both indoors and outdoors, "but the levels in general are close to the hearing and/or masking level." "In general the noise in the critical band up to 100 Hz is below both thresholds". The summary report notes that for road traffic noise (in the vicinity of roads) the low frequency noise levels are higher [than wind turbine] both indoors and outdoors.

5.5 Hayes McKenzie (2006)

Hayes McKenzie performed a study for the UK Department of Trade & Industry (DTI) to investigate complaints of low frequency noise that came from three of the five farms with complaints out of 126 wind farms in the UK. The study concluded that:

- Infrasound associated with modern wind turbines is not a source which will result in noise levels that are audible or which may be injurious to the health of a wind farm neighbor.
- Low frequency noise was measureable on a few occasions, but below DEFRA criteria. Wind turbine noise may result in indoor noise levels within a home that is just above the threshold of audibility; however, it was lower than that of local road traffic noise.
- The common cause of the complaints was not associated with low frequency noise but the occasional audible modulation of aerodynamic noise, especially at night. Data collected indoors showed that the higher frequency modulated noise levels were insufficient to awaken the residents at the three sights; however, once awake, this noise could result in difficulties in returning to sleep.

The UK Department of Trade and Industry, which is now the UK Department for Business Enterprise and Regulatory Reform (BERR), summarized the Hayes McKenzie report: "The report concluded that there is no evidence of health effects arising from infrasound or low frequency noise generated by wind turbines." [BERR (2007)]

5.6 Howe (2006)

Howe performed extensive studies on wind turbines and infrasound and concluded that infrasound was not an issue for modern wind turbine installations – "while infrasound can be generated by wind turbines, it is concluded that infrasound is not of concern to the health of residences located nearby." Since then Gastmeier and Howe (2008) investigated an additional situation involving the alleged "perception of infrasound by individual." In this additional case, the measured indoor infrasound was at least 30 dB below the perception threshold given by Watanabe and Moeller (1990) as presented in Table 4.3-3. Gastmeier and Howe (2008) also performed vibration measurements at the residence and nearest wind turbine, and concluded that the vibration levels were well below the perception limits discussed in ISO 2631-2.

5.7 Branco (2004)

Branco and other Portuguese researchers have studied possible physiological affects associated with high amplitude low frequency noise and have labeled these alleged effects as "Vibroacoustic Disease" (VAD). "Vibroacoustic disease (VAD) is a whole-body, systemic pathology, characterized by the abnormal proliferation of extra-cellular matrices, and caused by excessive exposure to low frequency noise." Hayes (2007, 2008) concluded that levels from wind farms are not likely to cause VAD after comparing noise levels from alleged VAD cases to noise levels from wind turbines in homes of complainers. Noise levels in aircraft in which VAD has been hypothesized are considerably higher than wind turbine noise levels. Hayes also concluded that it is "unlikely that symptoms will result through induced internal vibration from incident wind farm noise." [Hayes (2007)] Other studies have found no VAD indicators in environmental sound that have been alleged by VAD proponents. [ERG (2001)]

5.8 French National Academy of Medicine (2006)

French National Academy of Medicine recommended "*as a precaution* construction should be suspended for wind turbines with a capacity exceeding 2.5 MW located within 1500 m of homes." [emphasis added] However, this precaution is not because of definitive health issues but because:

- sound levels one km from some wind turbine installations "occasionally exceed allowable limits" for France (note that the allowable limits are long term averages)
- French prediction tools for assessment did not take into account sound levels created with wind speeds greater than 5 m/s.
- Wind turbine noise has been compared to aircraft noise (even though the sound levels of wind turbine noise are significantly lower), and exposure to high level aircraft noise "involves neurobiological reactions associated with an increased frequency of hypertension and cardiovascular illness. Unfortunately, no such study has been done near wind turbines." [Gueniot (2006)].

In March 2008, the French Agency for Environmental and Occupational Health Safety (AFSSET) published a report on "the health impacts of noise generated by wind turbines", commissioned by the Ministries of Health and Environment in June 2006 following the report of the French National Academy of Medicine in March 2006. [AFSSET (2008)] The AFSSET study recommends that one does not define a fixed distance between wind farms and homes, but rather to model the acoustic impact of the project on a case-by-case basis. One of the conclusions of the AFSSET report is: "The analysis of available data shows: The absence of identified direct health consequences concerning the auditory effects or specific effects usually associated with exposure to low frequencies at high level." ("L'analyse des données disponibles met en évidence: L'absence de conséquences sanitaires directes recensées en ce qui concerne les effets auditifs, ou les effets spécifiques généralement attachés à l'exposition à des basses fréquences à niveau élevé.")

6.0 REPRESENTATIVE WIND TURBINES

At the direction of NextEra, two types of utility-scale wind turbines were studied:

- General Electric (GE) 1.5sle (1.5 MW), and
- Siemens SWT-2.3-93 (2.3 MW).

Typical hub height for these wind turbines is 80 meters above ground level (AGL).

Sound levels for these wind turbine generators (WTGs) vary as a function of wind speed from cut-in wind speed to maximum sound level. Table 6.0-1 below lists the reference sound power levels of each WTG as a function of wind speed at 10 meters AGL as provided by the manufacturer. This is in conformance with the sound level standard for wind turbines [IEC 61400-11].

Table 6.0-1 Sound power levels as a Function of Wind Speed (dBA)

Wind Speed at 10 meters AGL (m/s)	GE 1.5 sle 80 m hub height; 77 m rotor diameter	Siemens SWT-2.3-93 80 m hub height; 92.4 m rotor diameter
3	<96	ND
4	<96	ND
5	99.1	99
6	103.0	103.4
7	≤104	104.9
8	≤104	105.1
9	≤104	105.0
10	≤104	105.0

ND = No Data available

Each wind turbine manufacturer applied the uncertainty factor K of 2 dBA to guarantee the turbine's sound power level. (According to IEC TS 61400-14, K accounts for both measurement variations and production variation.) The results in Section 8.0 use the manufacturer's guaranteed value, that is, 2 dBA above the levels in Table 6.0-1.

One-third octave band sound power level data have also been provided for each turbine reflective of the highest A-weighted level (typically a wind speed of 8 m/s or greater at 10 m AGL). These data are reference (not guaranteed) data, and are summarized below in Table 6.0-2. Cut-in wind speed for the GE 1.5 sle wind turbine is 3.5 m/s while the Siemens wind turbine has a cut-in wind speed of 4 m/s. The last two rows in Table 6.0-2 contain the overall A-weighted sound power levels from Table 6.0-1 and the guaranteed values.

Table 6.0-2 One-Third Octave Sound Power Levels at 8 m/s (un-weighted, dB)

1/3 Octave Band Center Frequency, Hz	GE 1.5 sle 80 m hub height; 77 m rotor diameter	Siemens SWT-2.3-93 80 m hub height; 92.4 m rotor diameter
25	ND	109.0
31.5	ND	105.7
40	ND	105.3
50	106.4	105.3
63	106.1	104.8
80	105.1	104.7
100	103.9	104.8
125	102.8	105.3
160	105.8	103.2
200	101.6	103.7
250	100.6	105.0
315	100.6	102.5
400	99.1	100.2
500	97.0	97.8
630	95.1	95.8
800	94.8	93.5
1000	92.8	92.7
1250	91.7	90.6
1600	90.5	88.2
2000	88.4	87.1
2500	85.8	85.6
3150	83.6	83.9
4000	81.2	82.1
5000	78.1	80.8
6300	76.0	79.9
8000	72.4	79.4
10000	73.3	80.0
Overall - Reference	104 dBA	105 dBA
Guaranteed	106 dBA	107 dBA

ND = No data provided.

7.0 FIELD PROGRAM

Real-world data were collected from operating wind turbines to compare to the low frequency noise guidelines and criteria discussed previously in Section 4.0. These data sets consisted of outdoor measurements at various reference distances, and concurrent indoor/outdoor measurements at residences within the wind farm. Epsilon determined all means, methods, and the testing protocol without interference or direction from NextEra. No limitations were placed on Epsilon by NextEra with respect to the testing protocol or upon the analysis methods.

7.1 GE 1.5sle and Siemens SWT-2.3-93

Field measurements were conducted in order to measure sound levels at operating wind turbines, and compare them to the guidelines and criteria discussed in this report. NextEra provided access to the Horse Hollow Wind Farm in Taylor and Nolan Counties, Texas in November 2008 to collect data on the GE 1.5 sle and Siemens SWT-2.3-93 wind turbines. The portion of the wind farm used for testing is relatively flat with no significant terrain. The land around the wind turbines is rural and primarily used for agriculture and cattle grazing. The siting of the sound level measurement locations was chosen to minimize local noise sources except the wind turbines and the wind itself.

Two noise consultants collected sound level and wind speed data over the course of one week under a variety of operational conditions. Weather conditions were dry the entire week with ground level winds ranging from calm to 28 mph (1-minute average). In order to minimize confounding factors, the data collection tried to focus on periods of maximum sound levels from the wind turbines (moderate to high hub height winds) and light to moderate ground level winds.

Ground level (2 meters AGL) wind speed and direction were measured continuously at one representative location. Wind speeds near hub height were also measured continuously using the permanent meteorological towers maintained by the wind farm.

A series of simultaneous interior and exterior sound level measurements were made at four houses owned by participating landowners within the wind farm. Two sets were made of the GE WTGs, and two sets were made of the Siemens WTGs. Data were collected with both windows open and windows closed. Due to the necessity of coordinating with the homeowners in advance, and reasonable restrictions of time of day to enter their homes, the interior/exterior measurement data sets do not always represent ideal conditions. However, enough data were collected to compare to the criteria and draw conclusions on low frequency noise.

Sound level measurements were also made simultaneously at two reference distances from a string of wind turbines under a variety of wind conditions. Using the manufacturer's sound level data discussed in Section 6.0, calculations of the sound pressure levels as a function of distance in flat terrain were made to aid in deciding where to collect data in the field. Based on this analysis, two distances from the nearest wind turbine were selected - 1000 feet and 1500 feet - and were then used where possible during the field program.

Distances much larger than 1,500 feet were not practical since an adjacent turbine string could be closer and affect the measurements, or would put the measurements beyond the boundaries of the wind farm property owners. Brief background sound level measurements were conducted several times during the program whereby the Horse Hollow Wind Farm operators were able to shutdown the nearby WTGs for a brief (20 minutes) period. This was done in real time using cell phone communication.

All the sound level measurements described above were attended by the noise consultants. One series of unattended overnight measurements was made at two locations for approximately 15 hours to capture a larger data set. One measurement was set up approximately 1,000 feet from a GE 1.5 sle WTG and the other was set up approximately 1,000 feet from a Siemens WTG. The location was chosen based on the current wind direction forecast so that the sound level equipment would be downwind for the majority of the monitoring period. By doing this, the program was able to capture periods of strong hub-height winds and moderate to low ground-level winds.

Ground-borne vibration measurements were made within the Horse Hollow Wind Farm. Measurements were made 400 feet and 1000 feet downwind from both GE 1.5 sle and Siemens 2.3 MW WTGs under full operation. In addition, background vibration measurements were made with the WTGs briefly shutdown.

7.2 Measurement Equipment

Ground level wind speed and direction were measured with a HOBO H21-002 micro weather station (Onset Computer Corporation). The data were sampled every three seconds and logged every one minute. All sound levels were measured using two Norsonic Model Nor140 precision sound analyzers, equipped with a Norsonic-1209 Type 1 Preamplifier, a Norsonic-1225 half-inch microphone and a 7-inch Aco-Pacific untreated foam windscreen Model WS7. The instrumentation meets the "Type 1 - Precision" requirements set forth in American National Standards Institute (ANSI) S1.4 for acoustical measuring devices. The microphone was tripod-mounted at a height of five feet above ground. The measurements included simultaneous collection of broadband (A-weighted) and one-third-octave band data (0.4 hertz to 20,000 hertz bands). Sound level data were primarily logged in 10-minute intervals to be consistent with the wind farm's Supervisory Control And Data Acquisition (SCADA) system which provides power output (kW) in 10-minute increments. A few sound level measurements were logged using 20-miute intervals. The meters were calibrated and certified as accurate to standards set by the National Institute of Standards and Technology. These calibrations were conducted by an independent laboratory within the past 12 months.

The ground-borne vibration measurements were made using an Instantel Minimate Plus vibration and overpressure monitor. A triaxial geophone inserted in the ground measured the particle velocity (PPV). Each measurement was 20 seconds in duration and all data were stored in memory for later retrieval.

8.0 RESULTS AND COMPARISON TO CRITERIA

Results from the field program are organized by wind turbine type. For each wind turbine type, results are presented per location type (outdoor or indoor) with respect to applicable criteria. Results are presented for 1,000 feet from the nearest wind turbine. Data were also collected at 1,500 feet from the nearest wind turbine which showed lower sound levels. Therefore, wind turbines that met the criteria at 1,000 feet also met it at 1,500 feet. Data were collected under both high turbine output and moderate turbine output conditions, and low ground-level wind speeds (defined as sound power levels 2 or 3 dBA less than the maximum sound power levels). The sound level data under the moderate conditions were equivalent to or lower than the high turbine output scenarios, thus confirming the conclusions from the high output cases. A-weighted sound power levels presented in this section (used to describe turbine operation) were estimated from the actual measured power output (kW) of the wind turbines and the sound power levels as a function of wind speed presented in Table 6.0-1 plus an adjustment factor of 2 dBA (correction from reference values to guaranteed values).

Outdoor measurements are compared to criteria for audibility, for UK DEFRA disturbance using equivalent outdoor levels, for rattle and annoyance criteria as contained in ANSI S12.9 Part 4, and for perceptible vibration using equivalent outdoor levels from ANSI/ASA S12.2. Indoor measurements are compared to criteria for audibility, for UK DEFRA disturbance, and for suitability of bedrooms, hospitals and schools and perceptible vibration from ANSI/ASA S12.2.

8.0.1 Audibility

The threshold of audibility criteria discussed in section 4.3.4 is used to evaluate wind turbine sound levels. The audibility of wind turbines both outdoors and indoors was examined.

8.0.2 UK DEFRA Disturbance Criteria

The DEFRA one-third octave band sound pressure level L_{eq} criteria and procedures for assessing disturbance from low frequency noise (see section 4.3.2) were examined. The indoor criteria and equivalent outdoor criteria were compared to measured low frequency noise from wind turbines.

8.0.3 Perceptible Vibration, Rattle and Annoyance – Outdoor Measurements

The ANSI/ASA S12.2 interior perceptible vibration criteria were converted to equivalent outdoor criteria as discussed in section 4.2.3 and compared to the measured low frequency noise from wind turbines. In addition, measured data were compared to ANSI S12.9 Part 4 low frequency sound levels for minimal annoyance and for the threshold for beginning of rattles as described in section 4.2.2.

8.0.4 ANSI/ASA S12.2 Low Frequency Criteria – Indoor Measurements

The ANSI/ASA S12.2 interior perceptible vibration criteria and low frequency portions of the room criteria for evaluating the suitability of noises in bedrooms, hospitals and schools were compared to indoor measurements of low frequency noise from wind turbines. (See section 4.2.3.)

8.1 Siemens SWT-2.3-93

8.1.1 Outdoor Measurements - Siemens SWT-2.3-93

Several periods of high wind turbine output and relatively low ground wind speed (which minimized effects of wind noise) were measured outdoors approximately 1,000 feet from the closest Siemens WTG. This site was actually part of a string of 15 WTGS, four of which were within 2,000 feet of the monitoring location. The sound level data presented herein include contributions from all wind turbines as measured by the recording equipment. The key operational and meteorological parameters during these measurements are listed in Table 8.1-1

Table 8.1-1 Summary of Operational Parameters – Siemens SWT-2.3-93 (Outdoor)

Parameter	Sample #34	Sample #39
Distance to nearest WTG	1,000 feet	1,000 feet
Time of day	22:00-22:10	22:50-23:00
WTG power output	1,847 kW	1,608 kW
Sound power	107 dBA	106.8 dBA
Measured wind speed @ 2 m	3.3 m/s	3.4 m/s
L_{Aeq}	49.4 dBA	49.6 dBA
L_{A90}	48.4 dBA	48.6 dBA
L_{Ceq}	63.5 dBC	63.2 dBC

8.1.1.1 Outdoor Audibility

Figure 8.1-1 plots the one-third octave band sound levels (L_{eq}) for both samples of high output conditions. The results show that infrasound is inaudible to even the most sensitive people 1,000 feet from these wind turbines (more than 20 dB below the median thresholds of hearing). Low frequency sound above 40 Hz may be audible depending on background sound levels.

8.1.1.2 UK DEFRA Disturbance Criteria – Outdoor measurements

Figure 8.1-2 plots the one-third octave band sound levels (L_{eq}) for both samples of high output conditions. The low frequency sound was "steady" according to DEFRA procedures, and the results show that all outdoor equivalent DEFRA disturbance criteria are met.

8.1.1.3 Perceptible Vibration, Rattle and Annoyance – Outdoor Measurements

Figure 8.1-3 plots the 16, 31.5, and 63 Hz octave band sound levels (L_{eq}) for both samples of high output conditions. The results show that all outdoor equivalent ANSI/ASA S12.2 perceptible vibration criteria are met. The low frequency sound levels are below the ANSI S12.9 Part 4 thresholds for the beginning of rattles (16, 31.5, 63 Hz total less than 70 dB), and the 31.5 and 63 Hz sound levels are below the level of 65 dB identified for minimal annoyance in ANSI S12.9 Part 4, and the 16 Hz sound level is within 1.5 dB of this level, which is an insignificant increase since the levels were not rapidly fluctuating.

8.1.2 Indoor Measurements - Siemens SWT-2.3-93

Simultaneous outdoor and indoor measurements were made at two residences at different locations within the wind farm to determine indoor audibility of low frequency noise from Siemens WTGs. In each house measurements were made in a room facing the wind turbines, and were made with either window open or closed. These residences are designated Homes "A" and "D" and were approximately 1,000 feet from the closest Siemens WTG. Both homes were near a string of multiple WTGS, four of which were within 2,000 feet of the house. The sound level data presented herein include contributions from all wind turbines as measured by the recording equipment. The key operational and meteorological parameters during these measurements are listed in Table 8.1-2.

Table 8.1-2 Summary of Operational Parameters – Siemens SWT-2.3-93 (Indoor)

Parameter	Home "A" (closed / open)	Home "D" (closed / open)
Distance to nearest WTG	1,060 feet	920 feet
Time of day	7:39-7:49 / 7:51-8:01	16:16-16:26 / 16:30 -16:40
WTG power output	1,884 kW / 1564 kW	2,301 kW / 2299 kW
Sound power	107 dBA / 106.7 dBA	107 dBA / 107 dBA
Measured wind speed @ 2 m	3.2 m/s / 3.7 m/s	9.6 m/s / 8.8 m/s
L_{Aeq}	33.8 dBA /38.1 dBA	35.0 dBA / 36.7 dBA
L_{A90}	28.1 dBA / 36.8 dBA	29.6 dBA / 31.2 dBA
L_{Ceq}	54.7 dBC / 57.1 dBC	52.8 dBC / 52.5 dBC

8.1.2.1 Indoor Audibility

Figure 8.1-4a plots the indoor one-third octave band sound levels (L_{eq}) for Home "A", and Figure 8.1-4b plots the indoor one-third octave band sound levels for Home "D". The results show that infrasound is inaudible to even the most sensitive people 1,000 feet from these wind turbines with the windows open or closed (more than 20 dB below the median thresholds of hearing). Low frequency sound at or above 50 Hz may be audible depending on background sound levels.

8.1.2.2 UK DEFRA Disturbance Criteria – Indoor Measurements

Figure 8.1-5a plots the indoor one-third octave band sound levels (L_{eq}) for Home "A". The low frequency sound was "steady" according to DEFRA procedures, and the results show that all outdoor equivalent DEFRA disturbance criteria are met. Figure 8.1-5b plots the indoor one-third octave band sound levels (L_{eq}) for Home "D". According to DEFRA procedures, the low frequency sound was not "steady" and therefore the data were compared to both criteria. The results show the DEFRA disturbance criteria were met for steady low frequency sounds, the DEFRA criteria were met for unsteady low frequency sounds except for the 125 Hz band, which was within 1 dB, which is an insignificant difference.

8.1.2.3 ANSI/ASA S12.2 Low Frequency Criteria – Indoor Measurements

Figure 8.1-6a plots the indoor 16 Hz to 125 Hz octave band sound levels (L_{eq}) for Home "A", and Figure 8.1-6b plots the indoor 16 Hz to 125 Hz octave band sound levels (L_{eq}) for Home "D". The results show the ANSI/ASA S12.2 low frequency criteria were easily met for both windows open and closed scenarios. The ANSI/ASA S12.2 low frequency criteria for bedrooms, classrooms and hospitals were met, the spectrum was balanced, and the criteria for moderately perceptible vibrations in light-weight walls and ceilings were also met.

8.2 GE 1.5sle

8.2.1 Outdoor Measurements - GE 1.5sle

Several periods of high wind turbine output and relatively low ground wind speed (which minimized effects of wind noise) were measured outdoors approximately 1,000 feet from the closest GE 1.5 sle WTG. This site was actually part of a string of more than 30 WTGS, four of which were within 2,000 feet of the monitoring location. The sound level data presented herein include contributions from all wind turbines as measured by the recording equipment. The key operational and meteorological parameters for these measurements are listed in Table 8.2-1.

Table 8.2-1 Summary of Operational Parameters – GE 1.5sle (Outdoor)

Parameter	Sample #46	Sample #51
Distance to nearest WTG	1,000 feet	1,000 feet
Time of day	23:10-23:20	00:00-00:10
WTG power output	1,293 kW	1,109 kW
Sound power	106 dBA	106 dBA
Measured wind speed @ 2 m	4.1 m/s	3.3 m/s
L_{Aeq}	50.2 dBA	50.7 dBA
L_{A90}	49.2 dBA	49.7 dBA
L_{Ceq}	62.5 dBC	62.8 dBC

8.2.1.1 Outdoor Audibility

Figure 8.2-1 plots the one-third octave band sound levels (L_{eq}) for both samples of high output conditions. The results show that infrasound is inaudible to even the most sensitive people 1,000 feet from these wind turbines (more than 20 dB below the median thresholds of hearing). Low frequency sound at and above 31.5 - 40 Hz may be audible depending on background sound levels.

8.2.1.2 UK DEFRA Disturbance Criteria – Outdoor measurements

Figure 8.2-2 plots the one-third octave band sound levels (L_{eq}) for both samples of high output conditions. The low frequency sound was "steady" according to DEFRA procedures, and the results show the low frequency sound meet or are within 1 dB of outdoor equivalent DEFRA disturbance criteria.

8.2.1.3 Perceptible Vibration, Rattle and Annoyance – Outdoor Measurements

Figure 8.2-3 plots the 16, 31.5, and 63 Hz octave band sound levels (L_{eq}) for both samples of high output conditions. The results show that all outdoor equivalent ANSI/ASA S12.2 perceptible vibration criteria are met. The low frequency sound levels are below the ANSI S12.9 Part 4 thresholds for the beginning of rattles (16, 31.5, 63 Hz total less than 70 dB), and the 16, 31.5, 63 Hz sound levels are below the level of 65 dB identified for minimal annoyance in ANSI S12.9 Part 4.

8.2.2 Indoor Measurements - GE 1.5sle

Simultaneous outdoor and indoor measurements were made at two residences at different locations within the wind farm to determine indoor audibility of low frequency noise from GE 1.5sle WTGs. In each house, measurements were made in a room facing the wind turbines, and were made with window either open or closed. These residences are designated Homes "B" and "C" and were approximately 1,000 feet from the closest Siemens WTG. Operational conditions were maximum turbine noise and high ground

winds at Home "B", and within 1.5 dBA of maximum turbine noise and high ground level winds at Home "C". Home "B" was near a string of multiple WTGs, four of which were within 2,000 feet of the house, while Home "C" was at the end of a string of WTGs, two of which were within 2,000 feet of the house. The sound level data presented herein include contributions from all wind turbines as measured by the recording equipment. The key operational and meteorological parameters during these measurements are listed in Table 8.2-2.

Table 8.2-2 Summary of Operational Parameters – GE 1.5sle (Indoor)

Parameter	Home "B" (closed / open)	Home "C" (closed / open)
Distance to nearest WTG	950 feet	1,025 feet
Time of day	9:29-9:39 / 9:40-9:50	11:49-11:59 / 12:00-12:10
WTG power output	1,017 kW / 896 kW	651 kW / 632 kW
Sound power	106 dBA / 105.8 dBA	104.7 dBA / 104.6 dBA
Measured wind speed @ 2 m	6.2 m/s / 6.8 m/s	6.4 m/s / 5.9 m/s
L_{Aeq}	27.1 dBA / 36.0 dBA	33.6 dBA / 39.8 dBA
L_{A90}	23.5 dBA / 33.7 dBA	27.6 dBA / 34.2 dBA
L_{Ceq}	47.1 dBC / 54.4 dBC	50.6 dBC / 55.1 dBC

8.2.2.1 Indoor Audibility

Figure 8.2-4a plots the indoor one-third octave band sound levels (L_{eq}) for Home "B", and Figure 8.2-4b plots the indoor one-third octave band sound levels for Home "C". The results show that infrasound is inaudible to even the most sensitive people 1,000 feet from these wind turbines with the windows open or closed (more than 20 dB below the median thresholds of hearing). Low frequency sound at and above 63 Hz may be audible depending on background sound levels.

8.2.2.2 UK DEFRA Disturbance Criteria – Indoor Measurements

Figure 8.2-5a plots the indoor one-third octave band sound levels (L_{eq}) for Home "B", and Figure 8.2-5b plots the indoor one-third octave band sound levels (L_{eq}) for Home "C". The results show the DEFRA disturbance criteria were met for steady and non-steady low frequency sounds.

8.2.2.3 ANSI/ASA S12.2 Low Frequency Criteria – Indoor Measurements

Figure 8.2-6a plots the indoor 16 Hz to 125 Hz octave band sound levels (L_{eq}) for Home "B", and Figure 8.2-6b plots the indoor 16 Hz to 125 Hz octave band sound levels (L_{eq}) for Home "C". The results show the ANSI/ASA S12.2 low frequency criteria were met for both windows open and closed scenarios. The ANSI/ASA S12.2 low frequency criteria for

bedrooms, classrooms and hospitals were met, the spectrum was balanced, and the criteria for moderately perceptible vibrations in light-weight walls and ceilings were also met.

8.3 Noise Reduction from Outdoor to Indoor

Simultaneous outdoor and indoor measurements were made at four residences within the Horse Hollow Wind Farm to determine noise reductions of the homes for comparison to that used in the determination of equivalent outdoor criteria for indoor criteria, such as ANSI/ASA S12.2 and DEFRA. Indoor measurements were made with windows open and closed. Tables 8.1-2 and 8.2-2 list the conditions of measurement for these houses.

The outdoor sound level data at Home "D" was heavily influenced by high ground winds – the measured levels were higher due to the effect of the wind on the microphone or the measurement of wind effect noise; therefore the data from Home "D" was not used in the comparison of noise reduction, since it would over estimate actual noise reduction.

Figures 8.3-1a and 8.3-1b present the measured one-third octave band noise reduction for the three homes with windows closed and open, respectively. Also presented in these same figures are the one-third octave noise reductions used in Section 4 of this report to obtain equivalent outdoor criteria for the indoor DEFRA criteria ("Table 4.3-1 Noise Reduction - Open Window"). It can be seen that for the window closed condition in Figure 8.3-1a, the measured noise reductions for all houses were greater than that used in our analysis as described in Section 4. For the open window case, the average of the three homes has a greater noise reduction than used in Section 4 and all houses at all frequencies have higher values with one minor exception. Only Home "A" at 25 Hz had a lower noise reduction (3dB), and this difference is not critical since the measured indoor sounds at 25 Hz at each of these home was significantly lower than the indoor DEFRA criteria. Furthermore, the outdoor measurements for both Siemens and GE wind turbines at 1000 feet under high output/high noise levels met the equivalent outdoor DEFRA criteria at 25 Hz.

Table 8.3-1 presents the measured octave band noise reduction for the three homes with windows closed and open, respectively. Also presented in Table 8.3-1 are the octave band noise reductions used in Table 4.2-2 of this report to obtain equivalent outdoor criteria for the indoor ANSI/ASA S12.2 criteria for perceptible vibration. It can be seen that for the window closed condition, the measured noise reductions for all houses were greater than that used in our analysis as described in Section 4. For the open window case, the average of the three homes has a greater noise reduction than used in Section 4 and all houses at all frequencies have higher values with one minor exception. Only Home "A" at 31 Hz (which contains the 25 Hz one-third octave band) had a lower noise reduction (3dB), and this difference is not critical since the measured indoor sounds at 31 Hz at each of these homes was significantly lower than the indoor ANSI/ASA S12.2 criteria. Furthermore, the outdoor measurements for both Siemens and GE wind turbines at 1000 feet under high output/high noise levels met the equivalent outdoor ANSI/ASA S12.2 criteria at 31 Hz.

Table 8.3-1 Summary of Octave Band Noise Reduction – Interior Measurements

Home	Wind Turbine	Windows	16 Hz	31.5 Hz	63 Hz
A	Siemens SWT-2-3-93	Closed	5	6	16
A	Siemens SWT-2-3-93	Open	4	3	12
B	GE 1.5 sle	Closed	20	22	22
B	GE 1.5 sle	Open	13	17	18
C	GE 1.5 sle	Closed	13	14	19
C	GE 1.5 sle	Open	8	13	17
Table 4.2-2 Noise Reduction		Open	3	6	9

8.4 Ground-Borne Vibration

Seven sets of ground-borne vibration measurements were made from Siemens 2.3 and GE 1.5sle wind turbines. The maximum ground-borne vibration RMS particle velocities were 0.071 mm/second (0.0028 inches/second) in the 8 Hz one-third octave band. This was measured 1000 feet downwind from a GE 1.5sle WTG under maximum power output and high wind at the ground. The background ground-borne vibration RMS particle velocity at the same location approximately 20 minutes beforehand was 0.085 mm/sec. Both of these measurements meet ANSI S2.71 recommendations for perceptible vibration in residences during night time hours. Soil conditions were soft earth representative of an active agricultural use. These vibration levels are nearly three orders of magnitude below the level of 0.75 inches/second set to prevent damage to residential structures. No perceptible vibration was felt from operation of the wind turbines. Measurements at the other sites and as close as 400 feet were significantly lower than the above measurements under high wind conditions.

Figure 8.1-1 Siemens SWT-2.3-93 Wind Turbine Outdoor Sound Levels at 1000 feet compared to Audibility Criteria

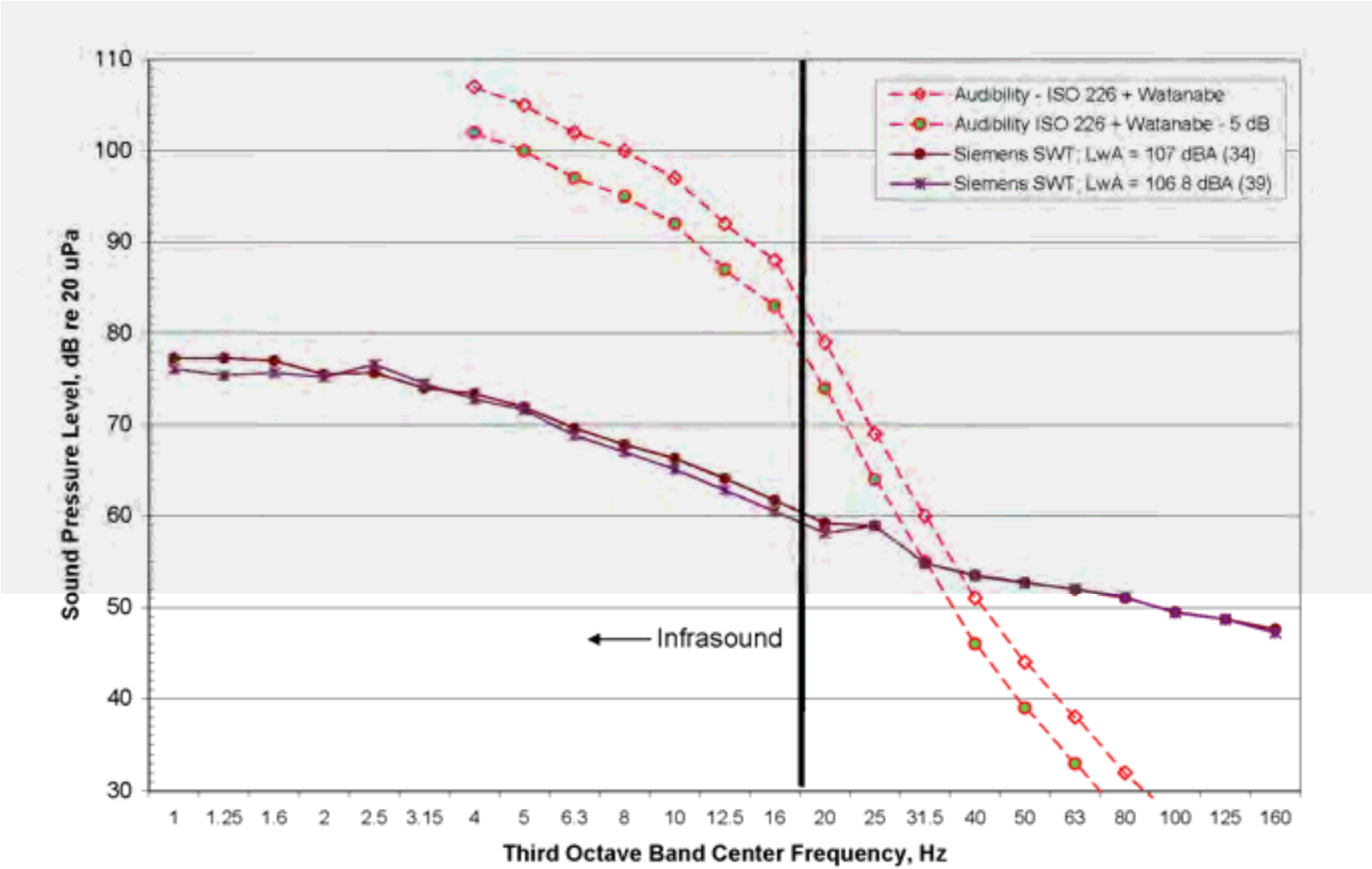


Figure 8.1-2 Siemens SWT-2.3-93 Wind Turbine Outdoor Sound Levels at 1000 feet compared to outdoor equivalent DEFRA Criteria

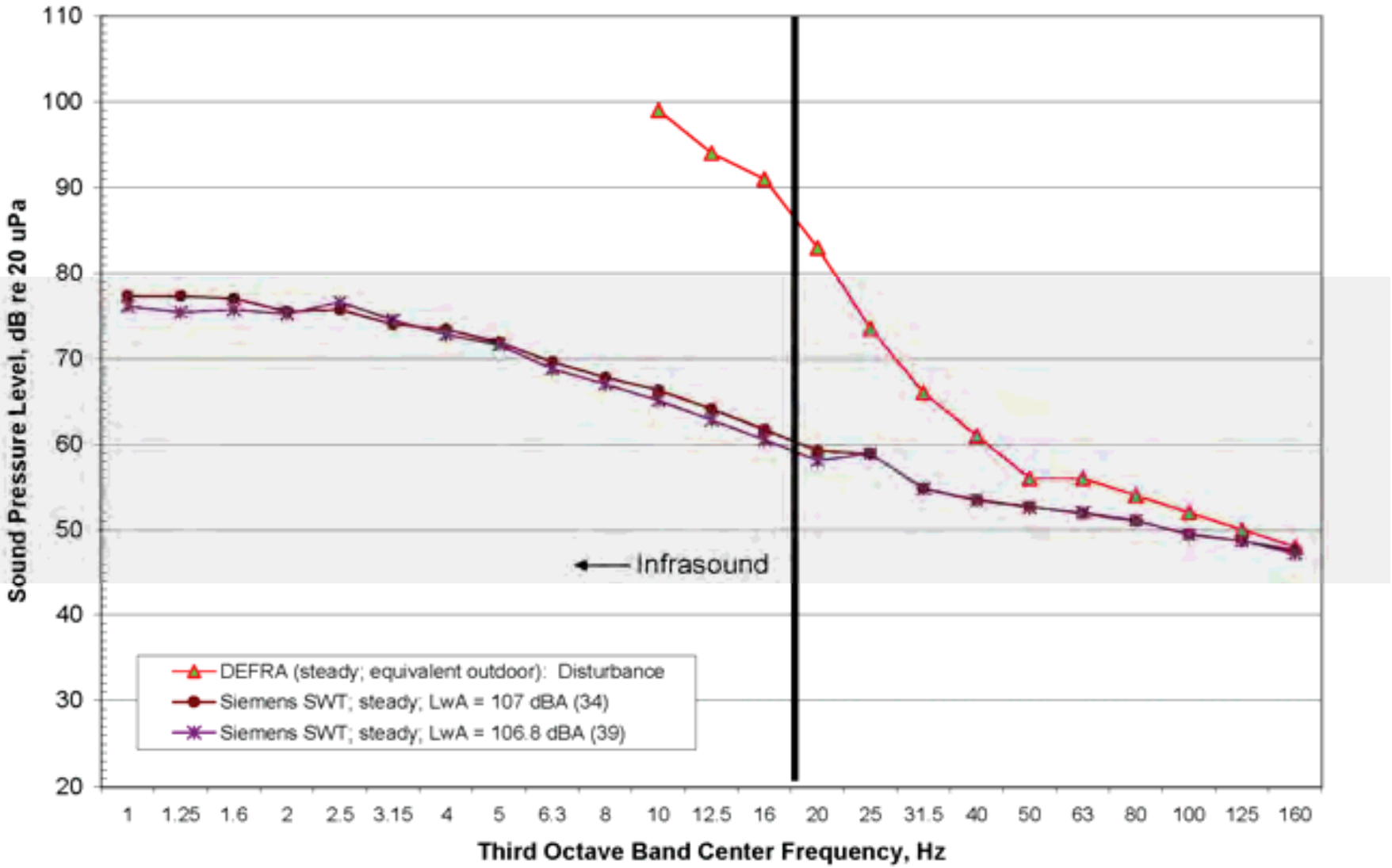


Figure 8.1-3 Siemens SWT-2.3-93 Wind Turbine Outdoor Sound Levels at 1000 feet compared to ANSI Criteria

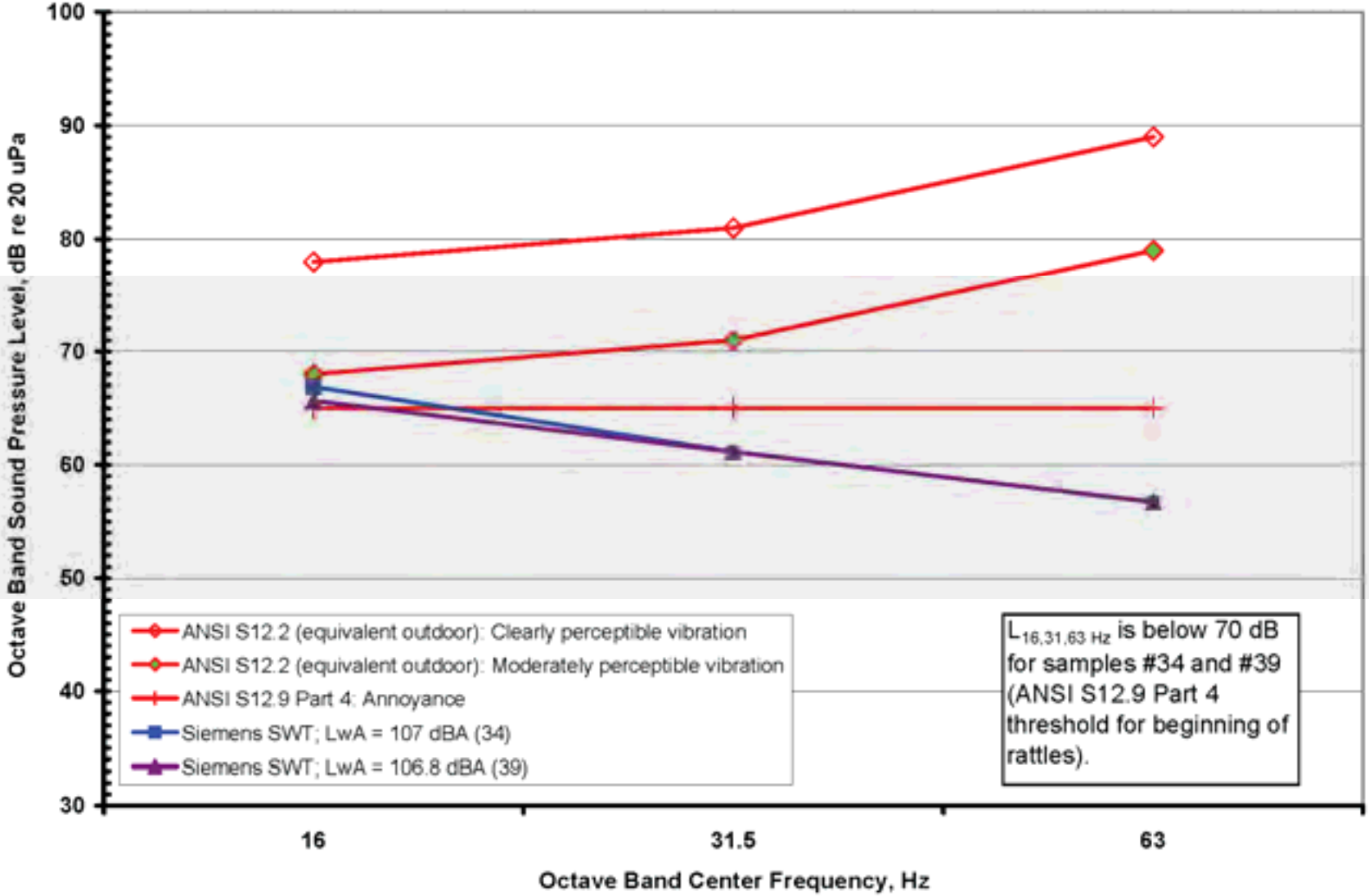


Figure 8.1-4a Siemens SWT-2.3-93 Wind Turbine Indoor Sound Levels at 1060 feet compared to Audibility Criteria (Home "A")

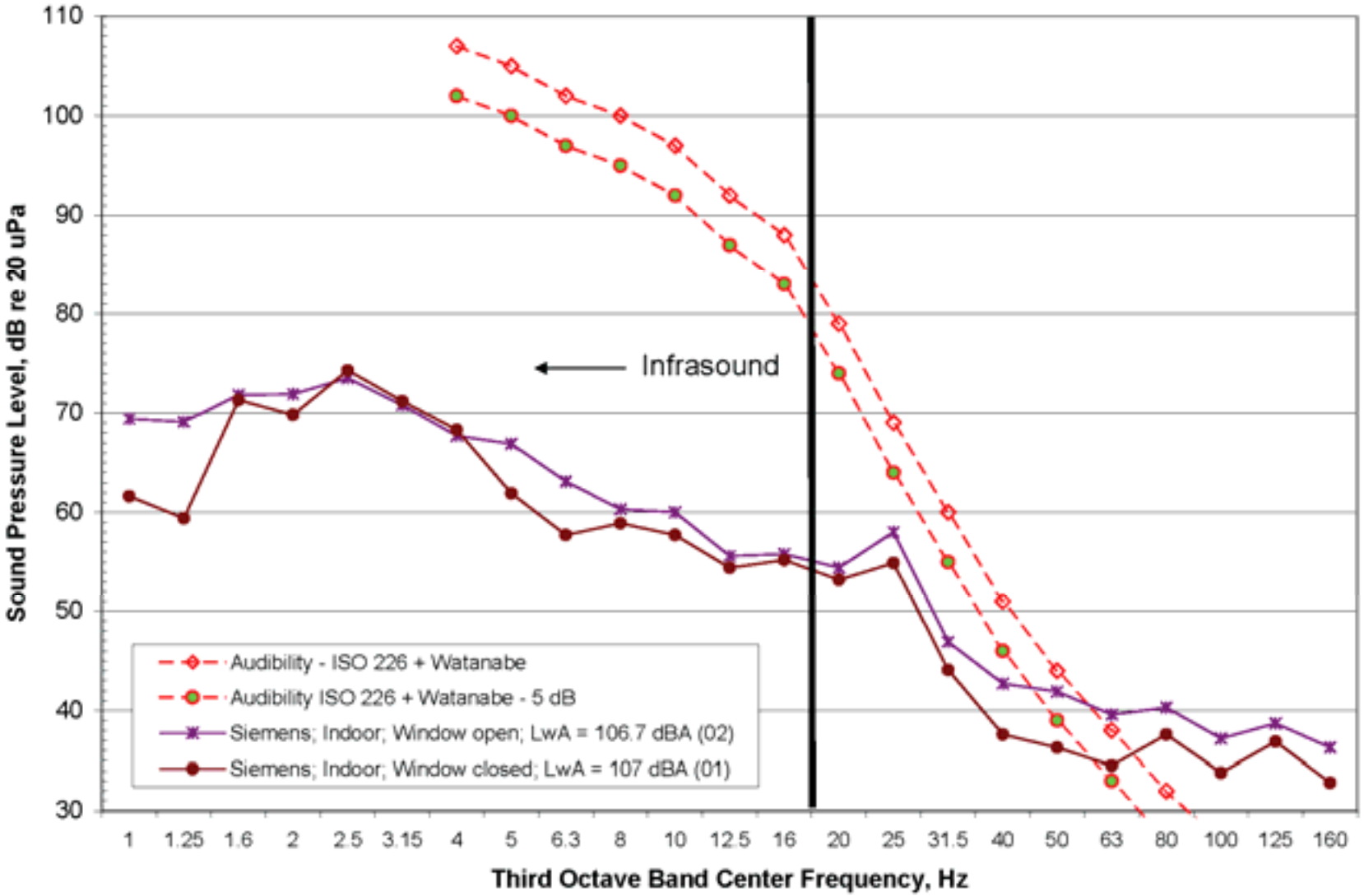


Figure 8.1-4b Siemens SWT-2.3-93 Wind Turbine Indoor Sound Levels at 920 feet compared to Audibility Criteria (Home "D")

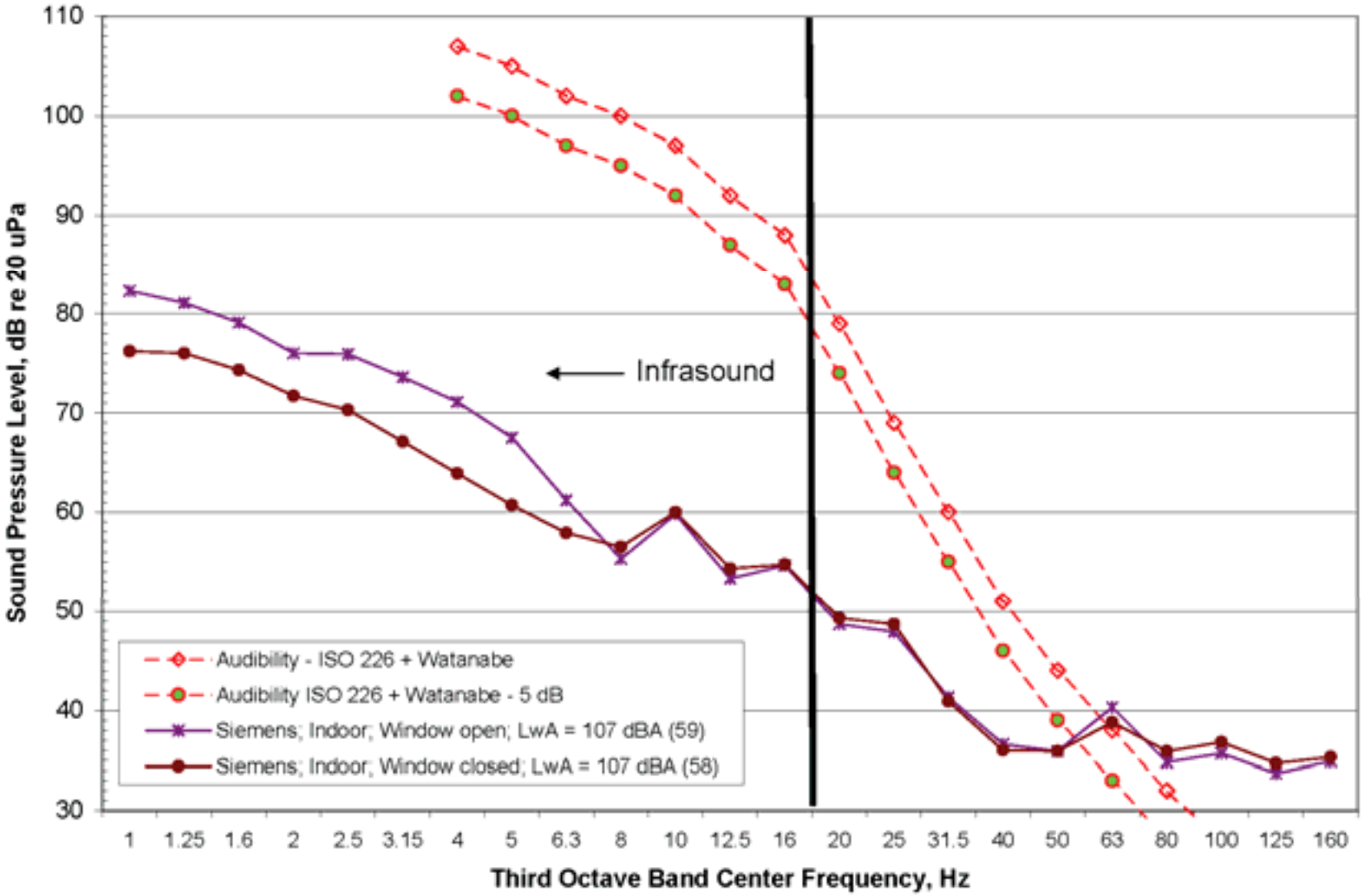


Figure 8.1-5a Siemens SWT-2.3-93 Wind Turbine Indoor Sound Levels at 1060 feet compared to DEFRA Criteria (Home "A")

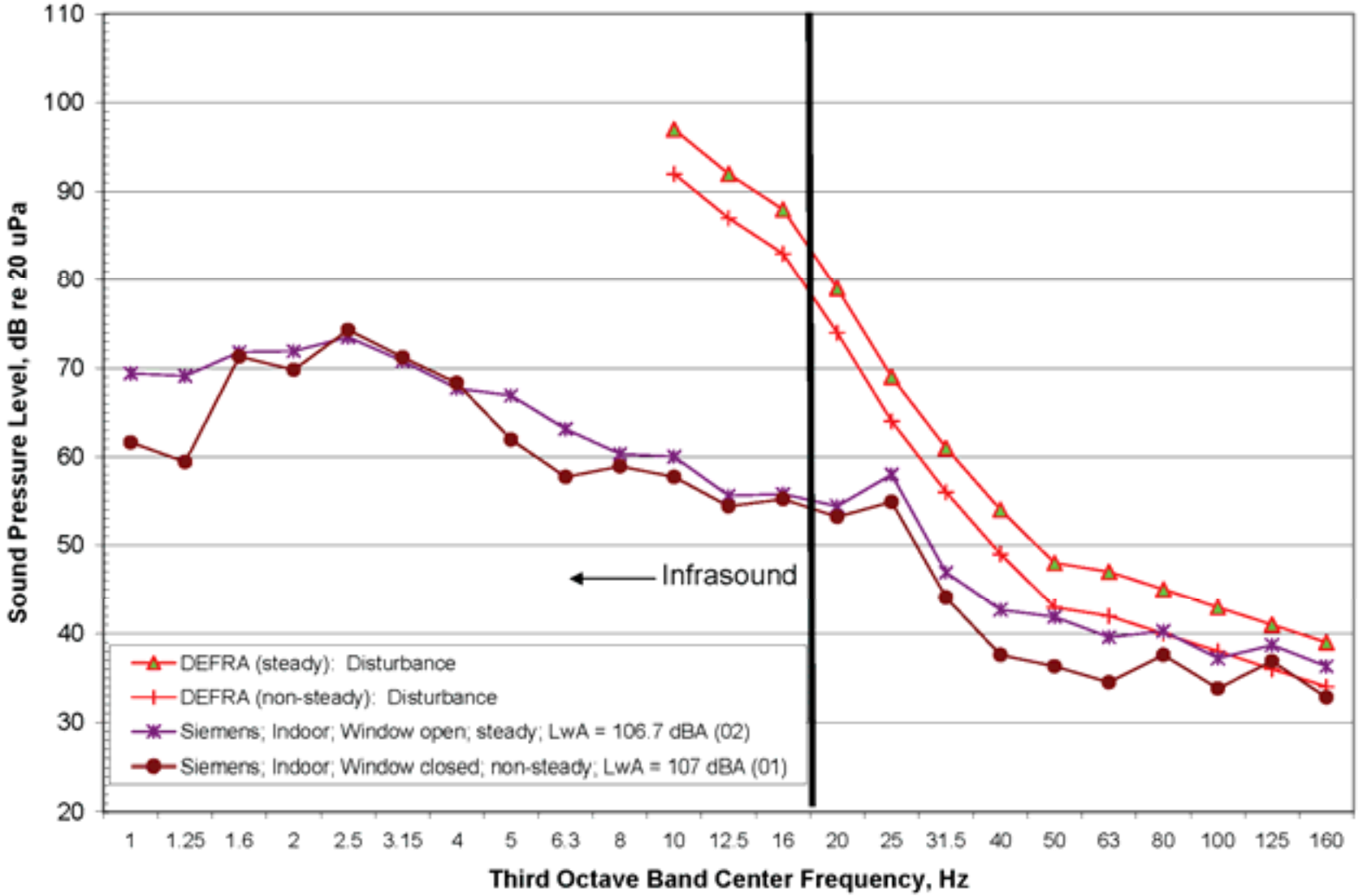


Figure 8.1-5b Siemens SWT-2.3-93 Wind Turbine Indoor Sound Levels at 920 feet compared to DEFRA Criteria (Home "D")

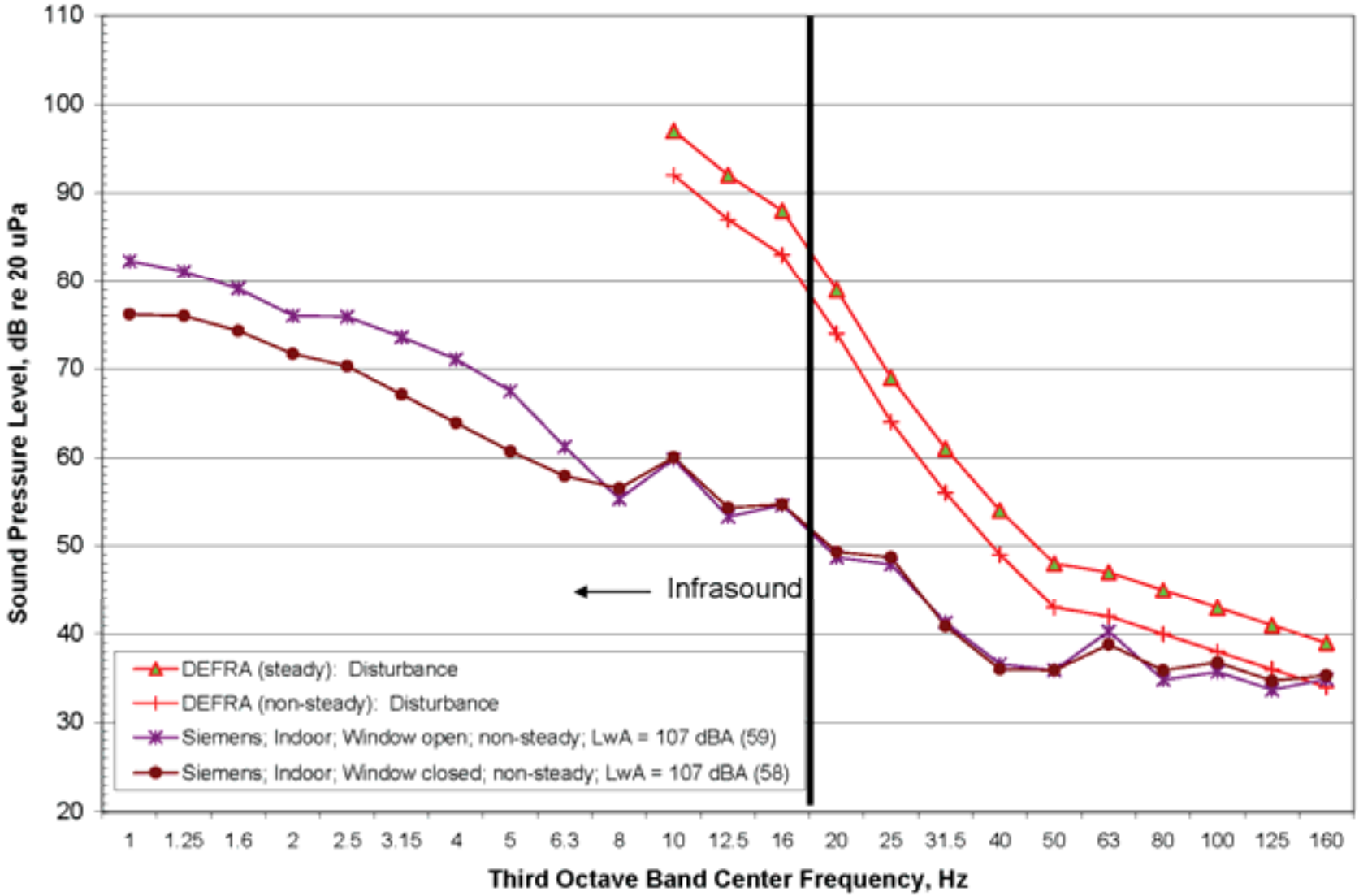


Figure 8.1-6a Siemens SWT-2.3-93 Wind Turbine Indoor Sound Levels at 1060 feet compared to ANSI 12.2 Criteria (Home "A")

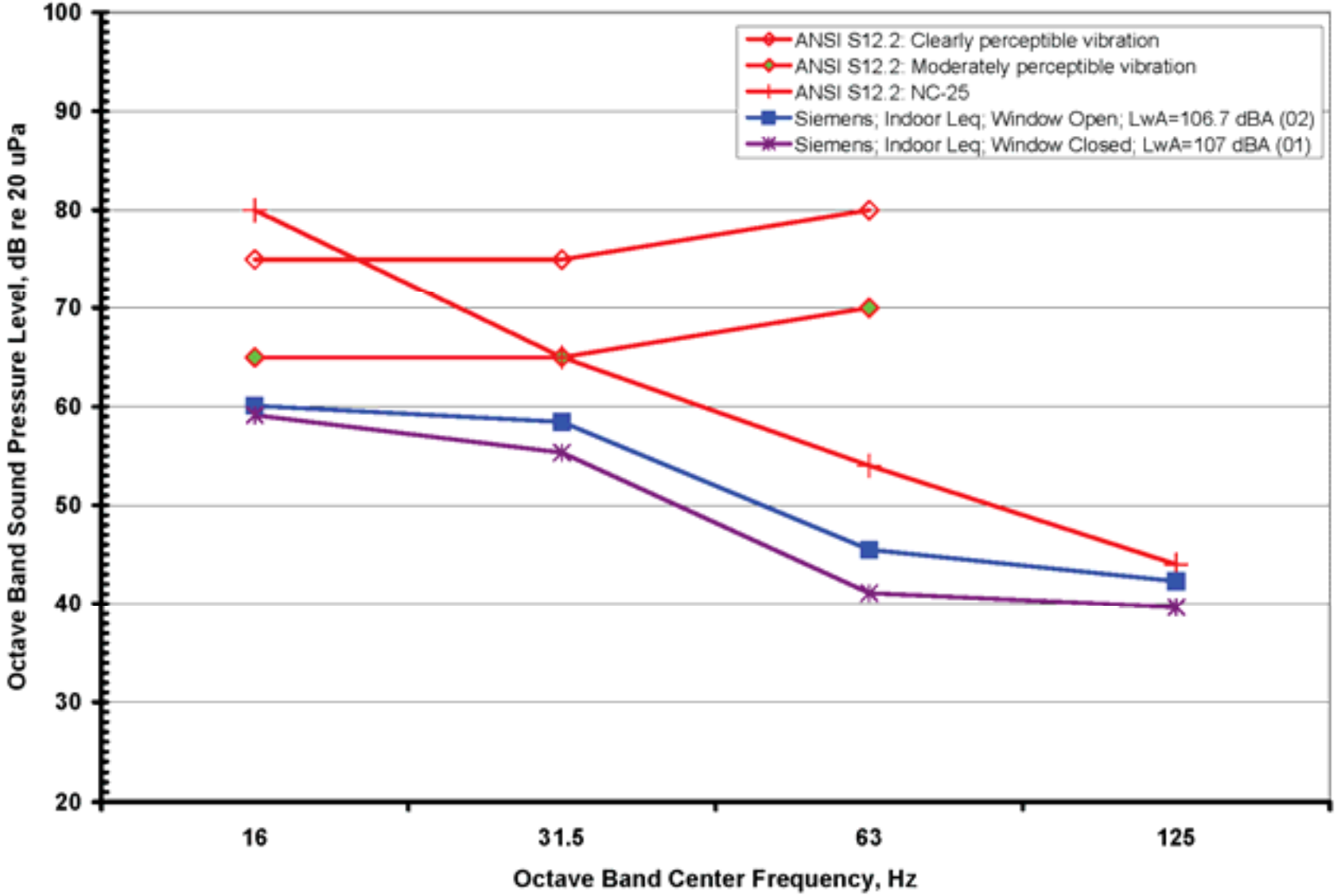


Figure 8.1-6b Siemens SWT-2.3-93 Wind Turbine Indoor Sound Levels at 920 feet compared to ANSI 12.2 Criteria (Home "D")

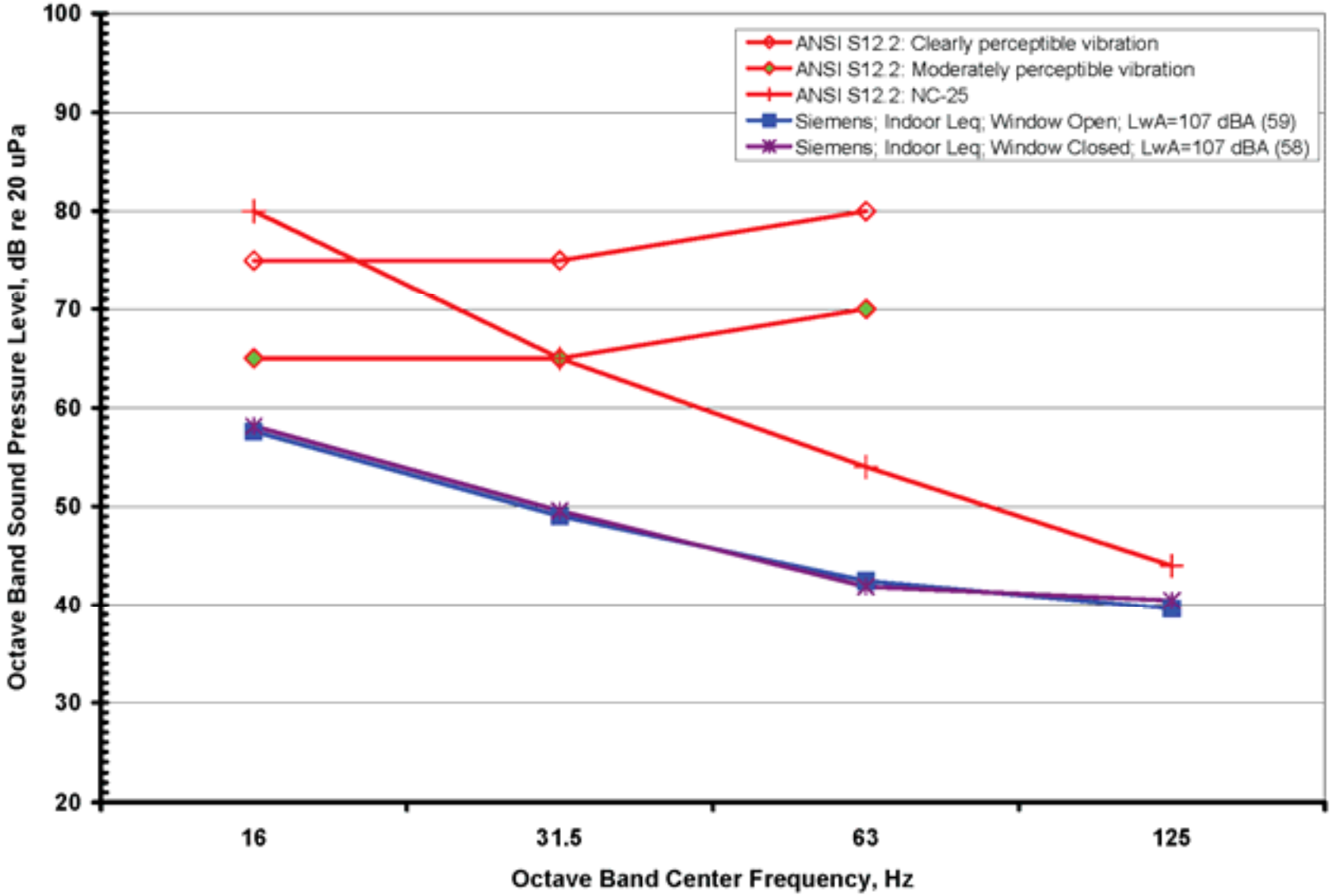


Figure 8.2-1 GE 1.5sle Wind Turbine Outdoor Sound Levels at 1000 feet compared to Audibility Criteria

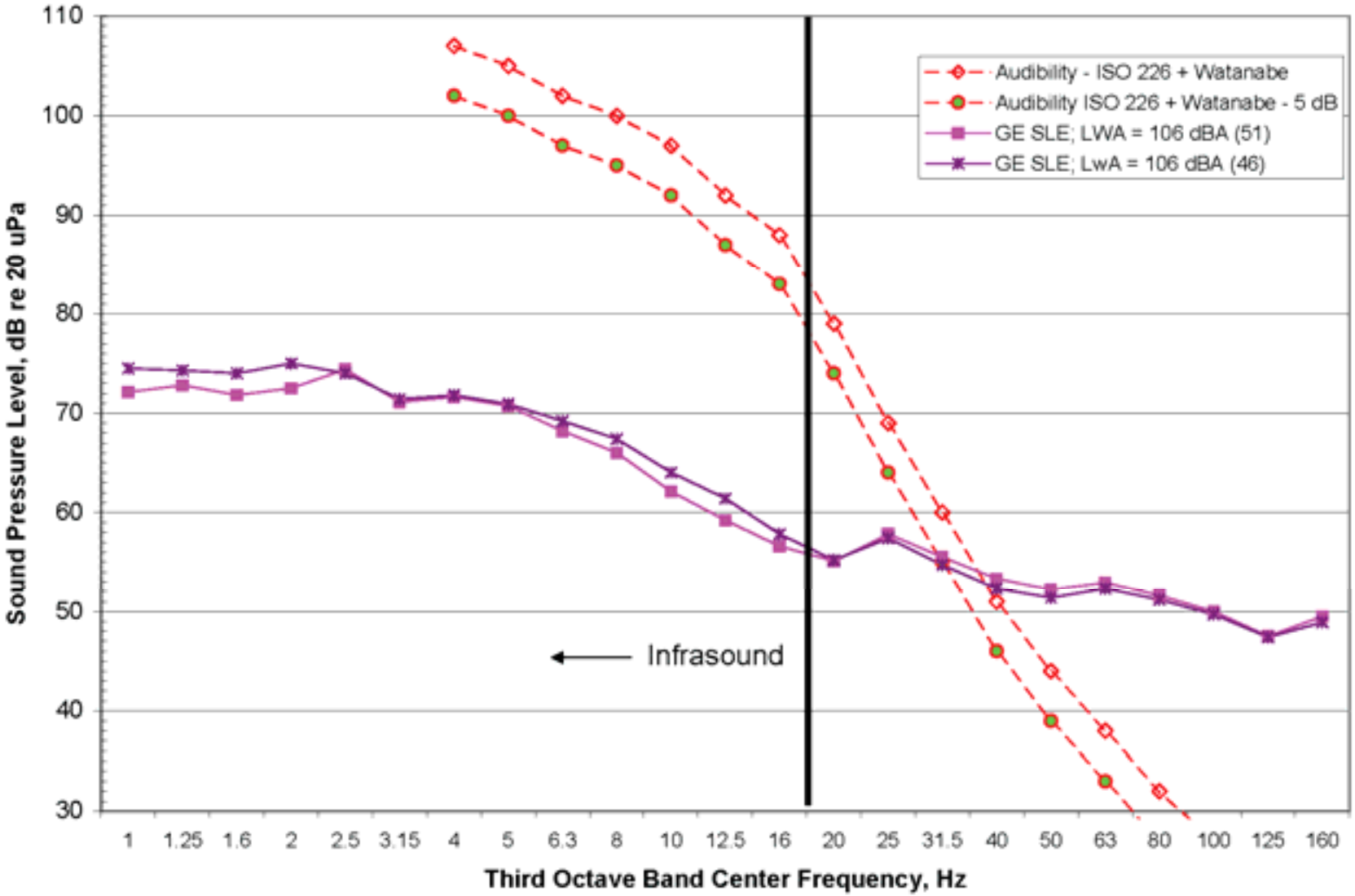


Figure 8.2-2 GE 1.5sle Wind Turbine Outdoor Sound Levels at 1000 feet compared to outdoor equivalent DEFRA Criteria

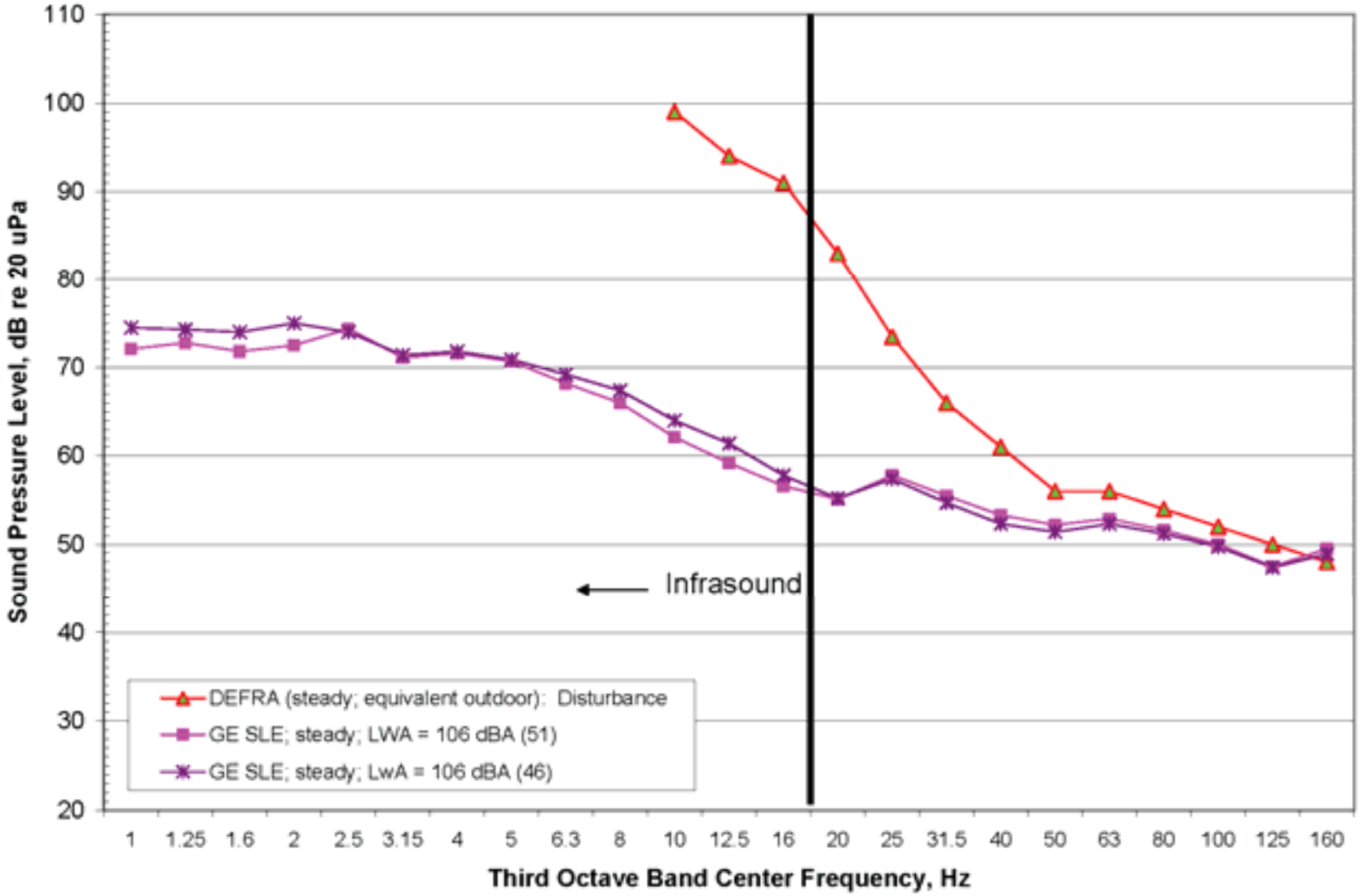


Figure 8.2-3 GE 1.5sle Wind Turbine Outdoor Sound Levels at 1000 feet compared to ANSI Criteria

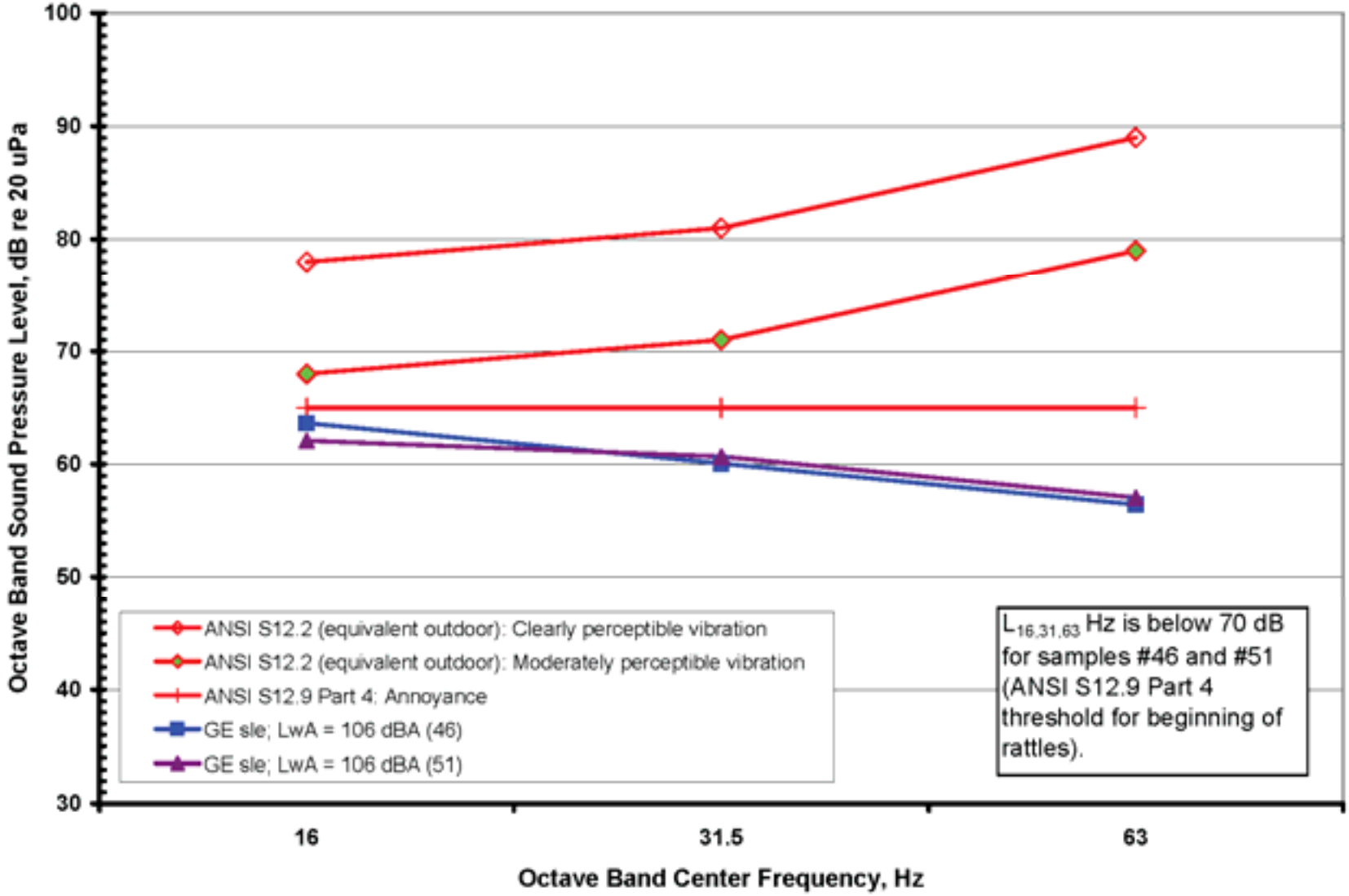


Figure 8.2-4a GE 1.5sle Wind Turbine Indoor Sound Levels at 950 feet compared to Audibility Criteria (Home "B")

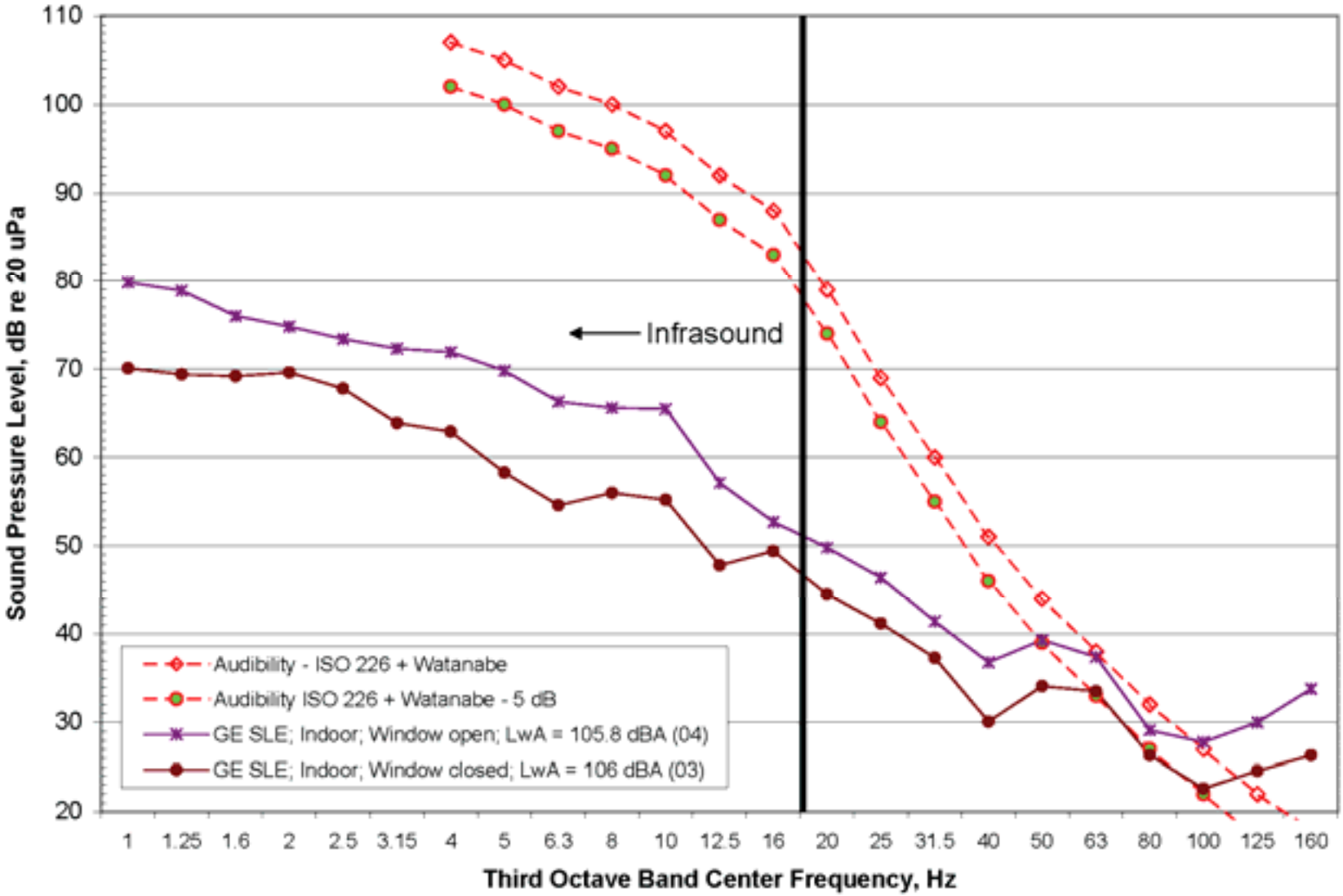


Figure 8.2-4b GE 1.5sle Wind Turbine Indoor Sound Levels at 1025 feet compared to Audibility Criteria (Home "C")

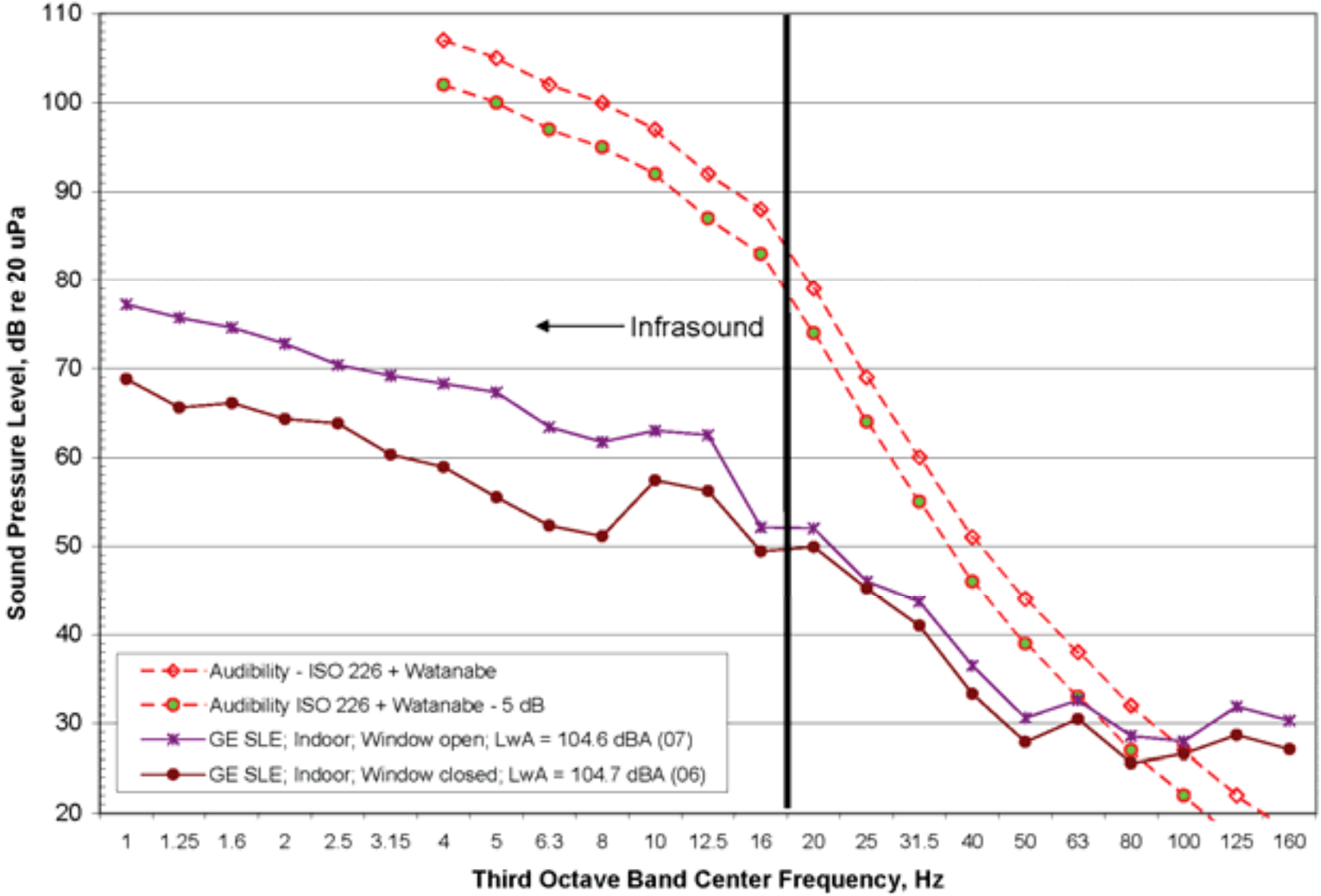


Figure 8.2-5a GE 1.5sle Wind Turbine Indoor Sound Levels at 950 feet compared to DEFRA Criteria (Home "B")

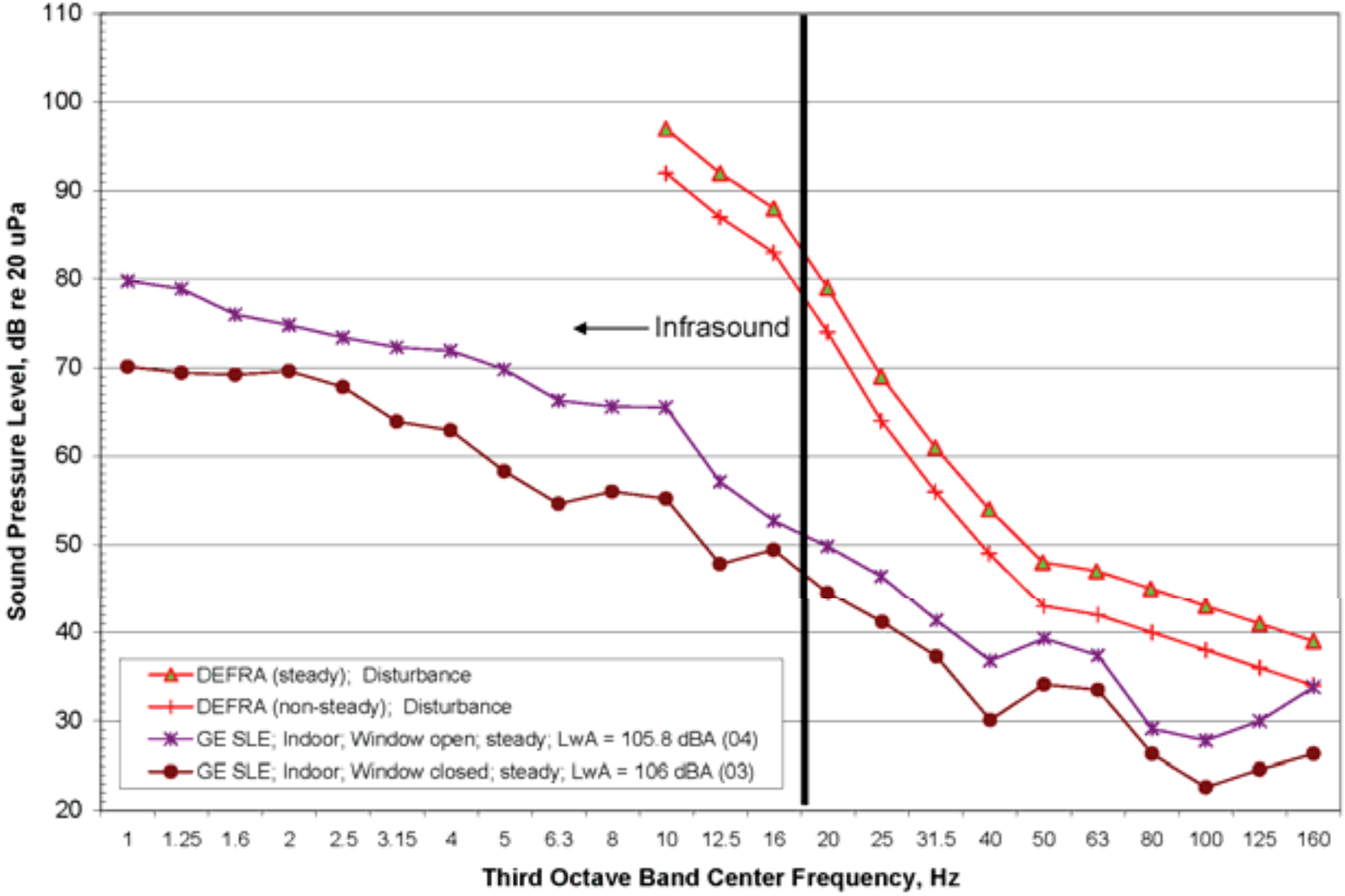


Figure 8.2-5b GE 1.5sle Wind Turbine Indoor Sound Levels at 1025 feet compared to DEFRA Criteria (Home "C")

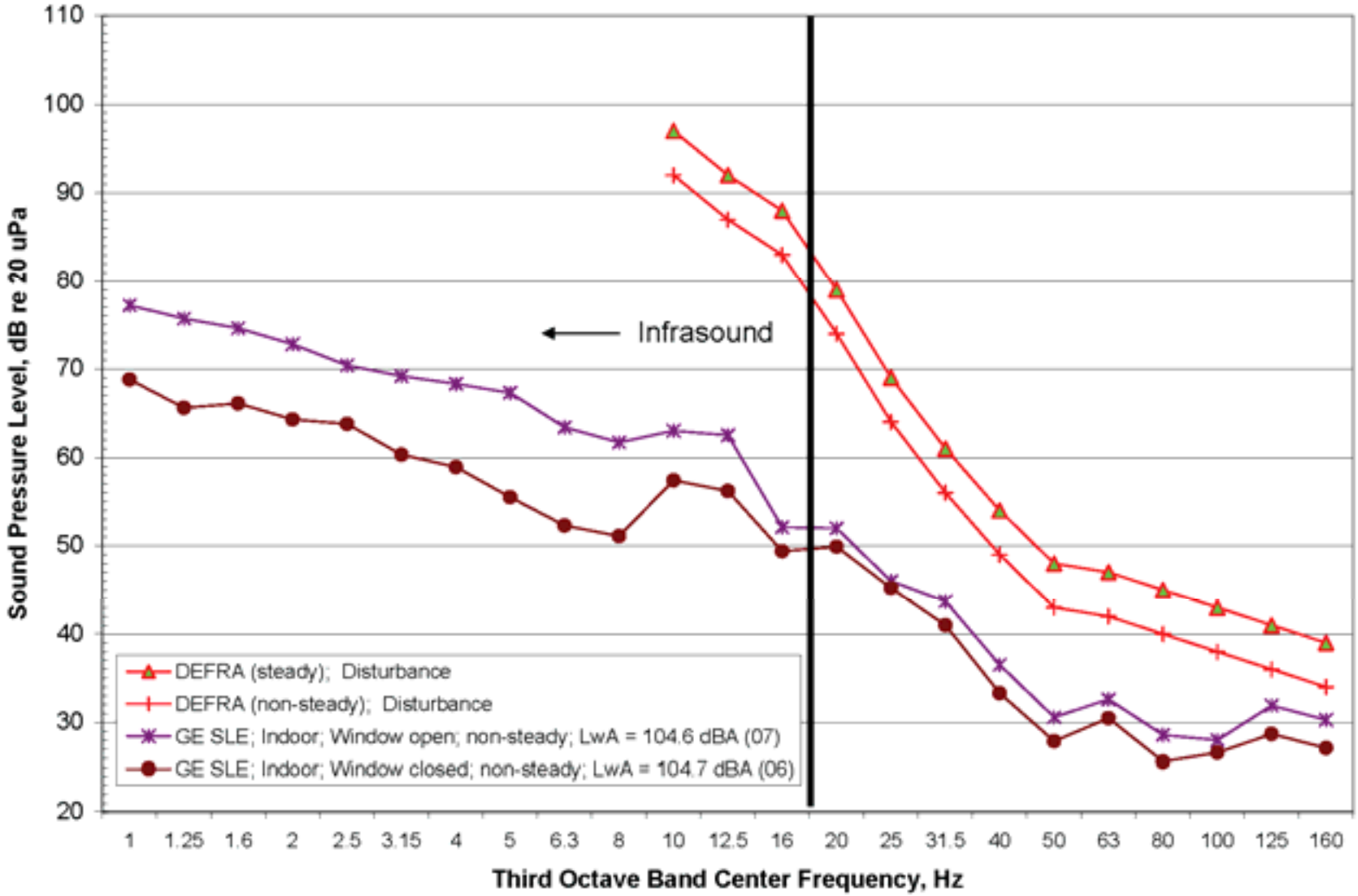


Figure 8.2-6a GE 1.5 sle Wind Turbine Indoor Sound Levels at 950 feet compared to ANSI 12.2 Criteria (Home "B")

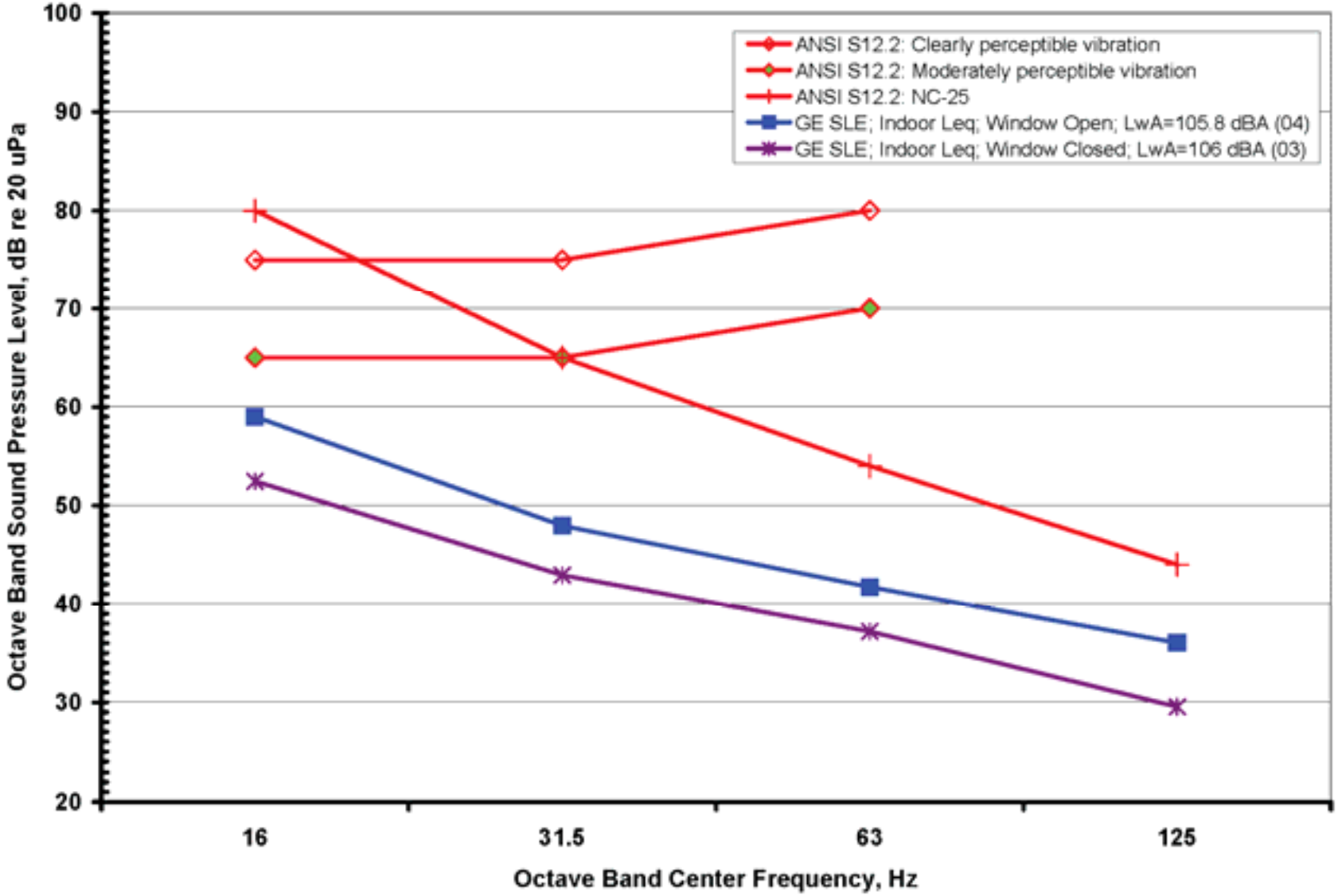


Figure 8.2-6b GE 1.5 sle Wind Turbine Indoor Sound Levels at 1025 feet compared to ANSI 12.2 Criteria (Home "C")

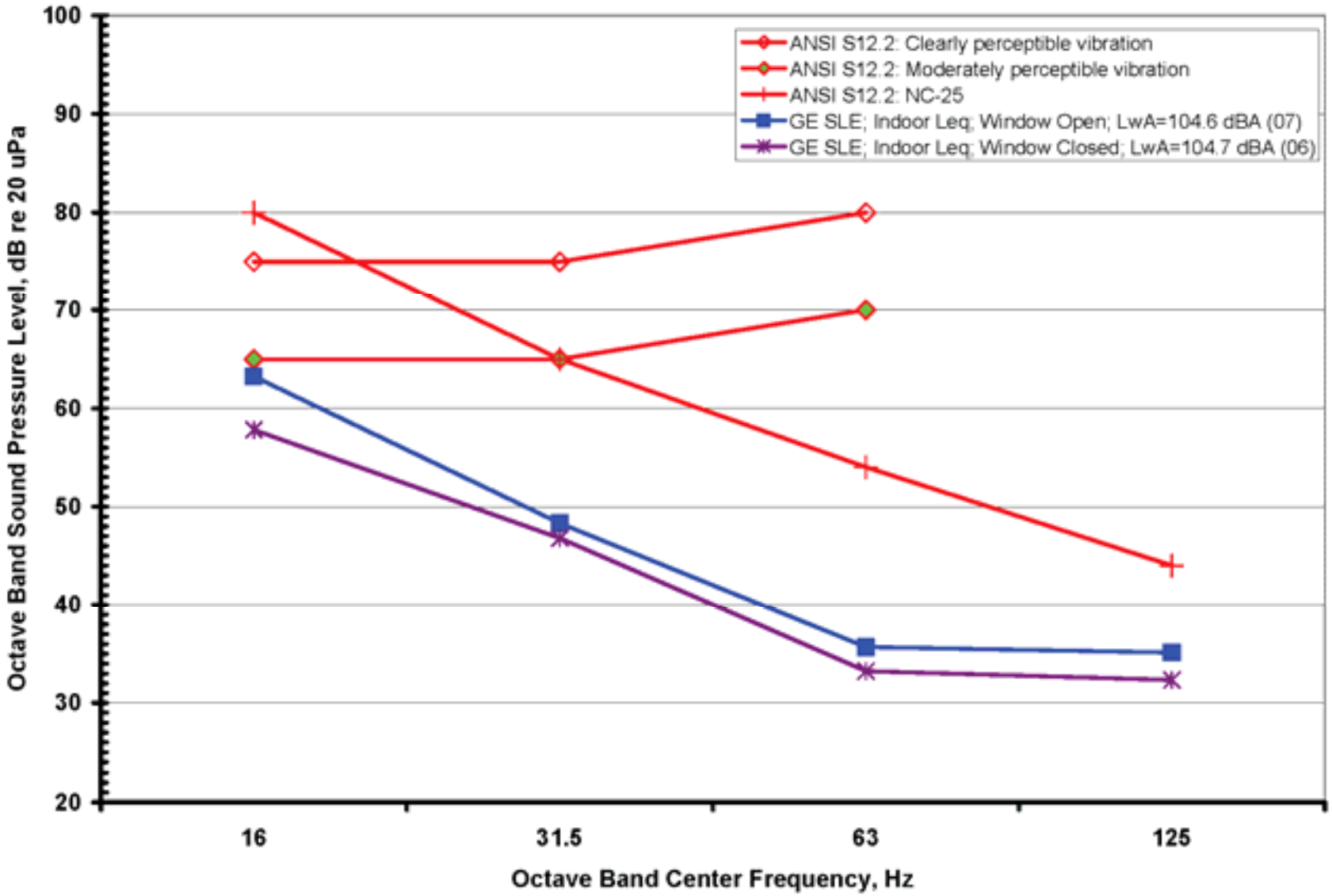


Figure 8.3-1a One-Third Octave Band Interior Noise Reduction – Windows Closed

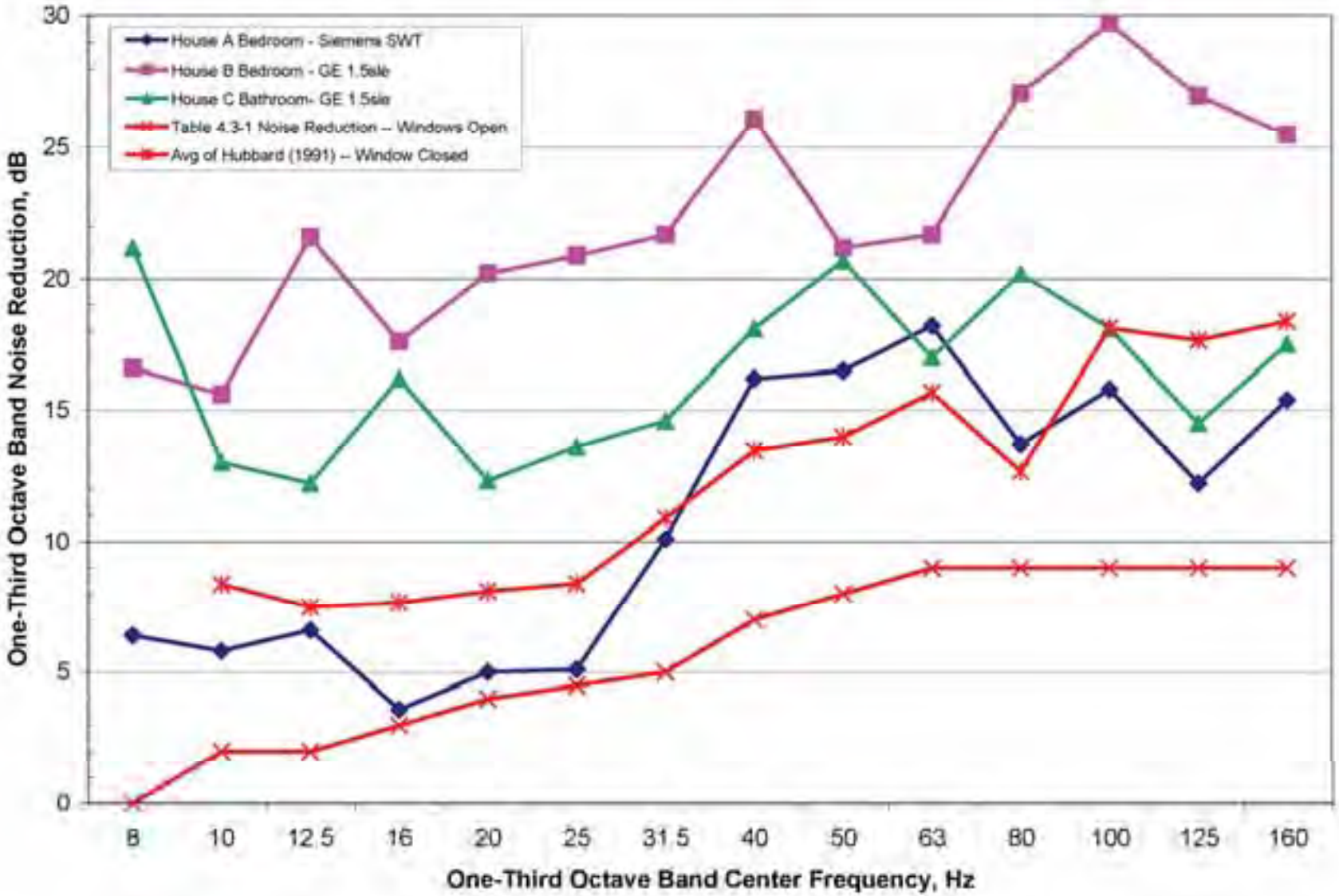
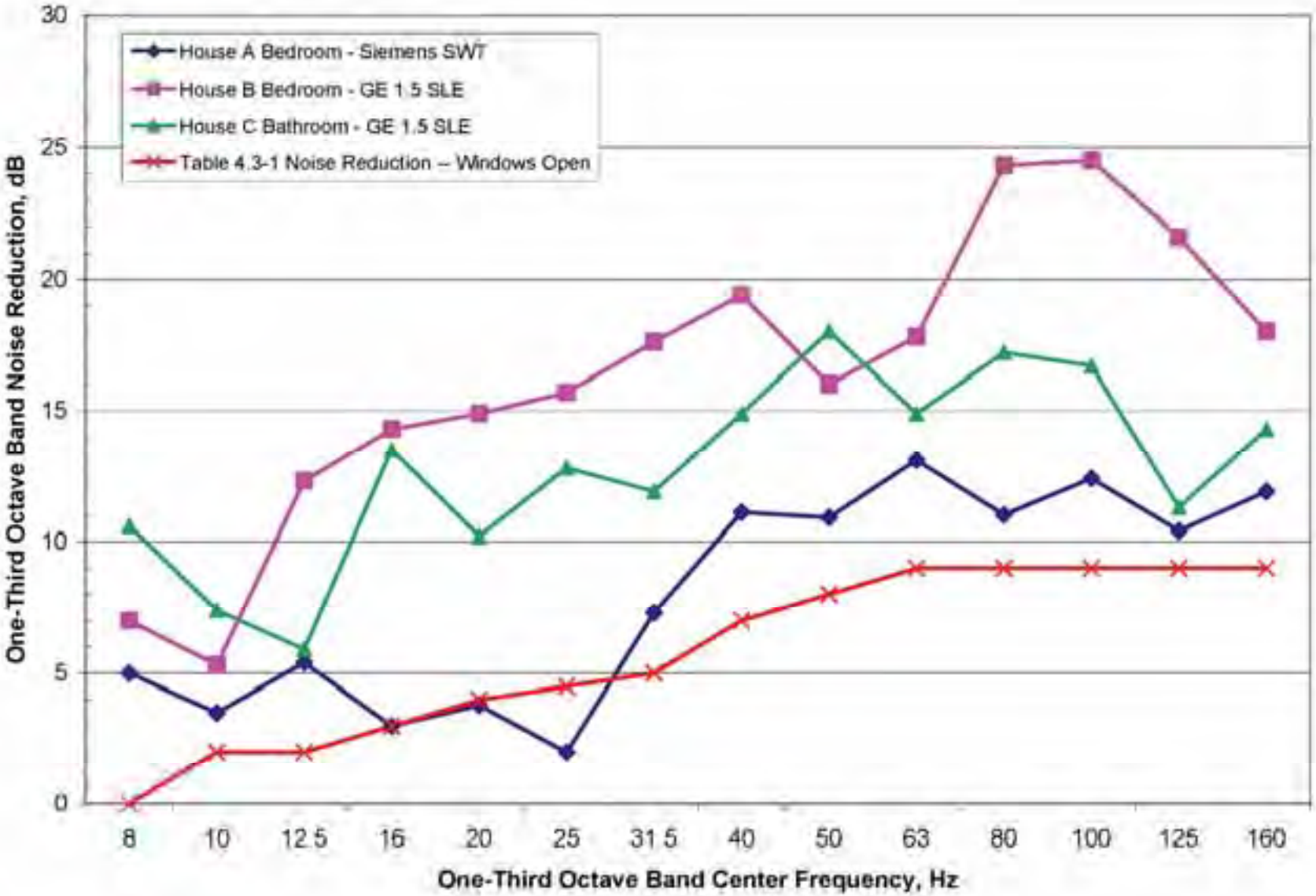


Figure 8.3-1b One-Third Octave Band Interior Noise Reduction – Windows Open



9.0 CONCLUSION

Siemens SWT 2.93-93 and GE 1.5sle wind turbines at maximum noise at a distance more than 1000 feet from the nearest residence do not pose a low frequency noise or infrasound problem. At this distance the wind farms:

- meet ANSI/ASA S12.2 indoor levels for low frequency sound for bedrooms, classrooms and hospitals;
- meet ANSI/ASA S12.2 indoor levels for moderately perceptible vibrations in light-weight walls and ceilings;
- meet ANSI S12.9 Part 4 thresholds for annoyance and beginning of rattles;
- meet UK DEFRA disturbance based guidelines;
- have no audible infrasound to the most sensitive listeners;
- might have slightly audible low frequency noise at frequencies at 50 Hz and above depending on other sources of low frequency noises in homes, such as refrigerators or external traffic or airplanes; and
- meet ANSI S2.71 recommendations for perceptible vibration in residences during night time hours.

In accordance with the above findings, and in conjunction with our extensive literature search of scientific papers and reports, there should be no adverse public health effects from infrasound or low frequency noise at distances greater than 1000 feet from the wind turbine types measured by Epsilon: GE 1.5sle and Siemens SWT 2.3-93.

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June 1, 2009

His Worship Mayor Randy Hope and Councillors
The Municipality of Chatham-Kent
315 King Street West
Chatham, ON N7M 5K8

Dear Mayor and Councillors:

Q S LA A N N AL S W ND N S

I am aware that Council has received a great deal of conflicting information on this issue, including health complaints in our own Municipality alleged to be caused by proximity to wind turbines. I will explain the position of the Health Unit that there is currently no substantial basis to conclude that wind turbines are directly eroding the health of people.

Evidence for medical conclusions is categorized into three levels, with level I providing the strongest evidence and level III the weakest.

- Level I: Evidence obtained from at least one properly designed randomized controlled trial.
- Level II-1: Evidence obtained from well-designed controlled trials without randomization.
- Level II-2: Evidence obtained from well-designed cohort or case-control analytic studies, preferably from more than one center or research group.
- Level II-3: Evidence obtained from multiple time series with or without the intervention. Dramatic results in uncontrolled trials might also be regarded as this type of evidence.
- Level III: Opinions of respected authorities, based on clinical experience, descriptive studies, or reports of expert committees.

Unfortunately, statistical analysis is limited with regard to wind turbine effects because of the paucity of level I and II evidence. Most of the so-called studies purporting to document adverse health effects caused by wind turbines are self-reported accounts or

open surveys of health issues that are nonspecific and common irrespective of wind turbine exposure, such as insomnia, hypertension, anxiety, digestive disturbances and subjective sensory changes. These accounts have been reported by the media and have created an impression in the public before a rigorous analysis has confirmed that there is either excess morbidity or an association with wind turbines. Uncontrolled self-reporting eliminates any chance of scientific analysis as there is no motivation or reason to report a lack of symptoms or a way to include all people in proximity to turbines. There is no mechanism to exclude people from participating in a self-reported survey multiple times. The boundaries of proximity are often not even defined. The lack of controls (a sample of people not exposed to wind turbines), failing to blind the surveyors (they should not know the exposure history before asking the questions) and not defining the study population result in what researchers call preselection bias. Similar surveys in the past have tended to distort and overestimate the prevalence of many things from “cancer clusters” to sexual practices (Kinsey’s infamous sex surveys). There is no local data on the prevalence of these symptoms before wind turbines were installed, so it cannot be determined whether or not there has been an increase. The most eloquent spokesman for the anti-wind turbine activists, former UWO Dean of Medicine Dr Robert McMurtry, has admitted that there are no controlled studies, and he has called on the province to conduct such a study. This has been supported by at least one Ontario Health Unit, but this would be methodologically difficult. It is not possible to design a study to conclusively prove a lack of association, such as that wind turbines cannot cause health effects or that there are no ghosts.

At the present time we have people who have concluded, with gut-felt certainty, that they have health problems caused by wind turbines. These reports have received a great deal of media attention and organized political action groups have been formed which advocate for government action to address these health problems and suspend the construction of wind farms. These objectors operate web sites and write letters which promulgate dubious explanations such as infrasound induced DNA alterations, “wind turbine syndrome”, coined by anti-wind turbine activist Dr Nina Pierpont of Malone, New York for a complex of nonspecific symptoms and “vibro-acoustic disease”, tissue fibrosis first ascribed to extreme sound and vibration exposure in aviation environments by Portuguese investigators Alves Pereira and Castelo Branco, but later associated with the much lower sound levels of wind turbines and even automobiles. No other researchers have confirmed these findings. Wind turbine syndrome and vibro-acoustic disease impress lay persons as legitimate diseases which account for how they are feeling, but neither is listed in the International Classification of Diseases nor is described in any standard medical textbook. Most experts are skeptical that they exist.

So can we make sense of these complaints?

Most health complaints regarding wind turbines have centered on sound as the cause. Three kinds of sound are emitted by wind turbines: infrasound (oscillation frequencies less than approximately 10 Hz), low frequency sound of approximately 10-200 Hz and

the fluctuating aerodynamic “swish” from the turbine blades which is also low frequency, approximately 500-1000 Hz.

Infrasound from natural sources (meteors, volcanic eruptions, ocean waves and wind) surrounds us and is below the audible threshold. The infrasound emitted from wind turbines is at a level of 50 to 70 dB, also well below the audible threshold. There is a consensus among acoustic experts that the infrasound from wind turbines is of no consequence whatsoever. A problem is that objectors often use the term infrasound incorrectly when they are referring to low frequency sounds.

Low frequency sounds below 40 Hz cannot be distinguished from background noise due to the wind itself. Perceptible (meaning above the background noise) low frequency noise can be produced by wind turbines under conditions of unusually turbulent wind conditions, but the actual sound level depends on the distance of the listener from the turbine, as the sound attenuates (falls off). The higher the frequency and the higher the temperature, the greater the sound attenuates with distance. Terrain and humidity are other factors. The low frequency noise emitted by spinning wind turbines could possibly be annoying to some when winds are unusually turbulent, but there is no evidence that this level of noise could be harmful to health. If so, city dwelling would be impossible due to the similar levels of ambient noise levels normally present in urban environments. It is not usually the low frequency nonfluctuating noise component that provokes complaints.

The fluctuating aerodynamic sound (swish) in the 500-1000 Hz range is from the wind turbine blades disturbing the air, modulated by the blades passing the tower which changes the sound dispersion characteristics in an audible manner. This fluctuating aerodynamic noise is the cause of most noise complaints regarding wind turbines, as it is harder to become accustomed to fluctuating noise than to noise that does not fluctuate. The noise limits imposed by the Ministry of the Environment for wind turbines are designed to prevent noise issues but some wind turbines produce noise levels that may be irritating and even stressful to some people who are more sensitive to noise. Sleep disturbance can occur. Others exposed to the same noise levels may experience no difficulty. There is no evidence of direct effects to health by this level of noise but there could be indirect effects from annoyance-induced stress. One paper categorically states that the only health effect of wind turbine noise is annoyance.[1]

There is a large body of medical literature on stress and psychoacoustics. There is a great deal of individual variation in the response to any given stimulus and legislated limits to noise and other annoyance factors are not designed to prevent problems in the most sensitive members of the population. Three factors that seem particularly

[1] Regan B., Casey T.G. Wind Turbine Noise Primer, Canadian Acoustics Special Issue, 34 (2) June 2006

pertinent to the discussion of wind turbine effects are the fear factor, also called the nocebo effect, and two medical conditions, sensory integration dysfunction and somatoform disorders.

The large volume of media coverage devoted to the alleged adverse health effects of wind turbines understandably creates an anticipatory fear in some that they will also experience adverse effects from wind turbines. Every person is suggestible to some degree. The resulting stress, fear and hypervigilance may exacerbate or even create problems which would not otherwise exist. In this way, anti-wind farm activists may be creating with their publicity some of the problems which they describe. This is the nocebo effect and it is the negative counterpart to the placebo effect where belief in an intervention may produce positive results.

Sensory integration dysfunction is a little-understood condition of abnormal sensitivity to any or all sensory stimuli (sound, touch, light, smell, taste). The afflicted experience unpleasant overpowering sensations to ambient conditions considered normal by most people. There is little data on the prevalence of this condition and it may be more common than is realized. Such individuals would be more sensitive to wind turbine noise than most.

Somatoform disorders are characterized by physical symptoms which reflect psychological states rather than physical causes. Conversion is the unconscious expression of stress and anxiety as a physical symptom and it is very common. Common conversion symptoms are vague sensations of tingling or discomfort, fatigue, poorly localized abdominal pain, headaches, back or neck pain, weakness, loss of balance, hearing and visual abnormalities. The wind turbine controversy has raised the rhetoric to stressful levels, and the similarities of human stress responses and conversion symptoms to those described as so-called wind turbine syndrome are striking.

In summary, there is no scientifically valid evidence that wind turbines are causing direct health effects, although the body of valid evidence is limited. It is unlikely that evidence of adverse health effects will emerge in the future because there is no biologically plausible mechanism known by which wind turbines could cause health effects. There are wind turbines in urban environments, including Toronto, that have not been causing problems. The European experience would indicate that wind farms can be compatible with rural environments. An annoyance factor undoubtedly exists to which there is individual variability. Associated stress from annoyance, exacerbated by all the negative publicity, is the likely cause for the purported erosion of health that some people living near rural wind turbines are reporting. Stress has multiple causes and is additive.

Unfortunately, there has been some misunderstanding regarding the role of the Medical Officer of Health and the Health Unit in these matters. It is beyond the scope of the

Chatham-Kent Health Unit to address this in any but a general manner. In my opinion the issue of wind turbine noise and associated stress needs to be managed at the Provincial level. If the Ministry of the Environment noise guidelines for wind turbine installations are exceeded, affected people have the option to pursue compensation, but the Chatham-Kent Board of Health has confirmed that it is not the role of the Health Unit to become involved in private litigation matters. From the outset, when requested by Council, the Health Unit and I have attempted to provide a balanced, evidence-based and scientifically valid appraisal of this whole situation to Council. As a result, anti-wind farm activists have attacked me personally on internet sites, accused me of being financially influenced by wind turbine manufacturers (untrue) and even made complaints about my conduct to regulatory bodies. Letters to the Chatham Daily News have castigated me for neglecting the health of Chatham-Kent citizens with the kind of inflammatory phrases spoken, it seems to me, in the language of people with a higher regard for their own convictions than for the facts.

Sincerely,

W. David Colby, MSc, MD, FRCPC
Acting Medical Officer of Health
Chatham-Kent Health Unit

Encl.:

Ramakrishnan R. Acoustic Consulting Report for the Ontario Ministry of the Environment, December 2007.

Leventhall, G. Infrasound from Wind Turbines – Fact, Fiction or Deception, Canadian Acoustics Special Issue 34(2), June 2006.

ACOUSTIC CONSULTING REPORT
Prepared for the Ontario Ministry of the Environment

WIND TURBINE FACILITIES NOISE ISSUES

Aiolos Report Number: 4071/2180/AR155Rev3
DECEMBER 2007

Author Ramani Ramakrishnan, Ph. D., P. Eng.
Lead Acoustician

Signature
Date: 28 December 2007

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AIOLOS ENGINEERING CORPORATION

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EXECUTIVE SUMMARY

All proponents of a wind farm development need to apply for a Certificate of Approval from the Ministry of the Environment of Ontario. The noise assessment report required for the approval process uses the guideline Ministry document, "Interpretation for Applying MOE NPC Technical Publications to Wind Turbine Generators" released in 2004. The above guidance document was to assist proponents of wind turbine installations in determining the list of necessary information to be submitted when applying for a Certificate of Approval (Air and Noise) under Section 9 of the *Environmental Protection Act*. The noise guidelines in MOE publications NPC-205/NPC-232 as well as the wind generated noise levels were applied to set the noise limits.

The Ministry has now initiated a review of the interpretation of the above policies, due to expanding body of knowledge of the noise impacts of wind turbines. The main aim of the proposed review is to assess the appropriateness of the Ministry's approach to regulating noise impacts of wind turbines.

The scope and requirements of the review can be summarized as: a) Review of the 2006 doctoral dissertation by van den Berg; b) Review of available noise policies and guidelines; review of relevant scientific literature; and review of MOE's current noise policies as applied to wind turbine noise and c) Provide expert opinion based on the above findings; and d) Prepare a report that provides advice on the state of the science regarding wind turbine noise, and on MOE policies and procedures that relate to wind turbine facilities. The results of the investigations are described below.

Van den Berg's research was initiated as a result of complaints, in Netherlands, against an existing wind farm in Germany very close to the Dutch border. The main hypotheses of the research are: a) atmospheric stability, particularly stable and very stable conditions happen mostly at night time and the hub-height wind speeds can be higher than those predicted from the 10 m high wind speeds using standard methods, such as the logarithmic profiles of the IEC standard. And hence, the wind turbine noise levels can be higher than expected. It was also conjectured that these discrepancies are prevalent during summer months; and b) beat-sounds

can become very pronounced during stable and very stable conditions. Although, the data of van den Berg's research did not provide conclusive scientific evidence to support the above hypotheses, further review of the literature showed that some of the basic conjectures may well be true. Hence, the research of van den Berg must be considered as the catalyst that started serious discussion on many noise aspects of wind farm. Future research must therefore provide strong scientific data to validate these different noise concerns.

The noise policies from different Canadian provinces, USA states and a few other countries were reviewed. General comparison of the noise regulations was presented. The main differences between the different regulations seem to be: i) in the acceptable noise limits; and ii) in the evaluation of receptor noise levels from the cumulative operation of the turbines in the wind farm. Further, some jurisdictions have special legislation concerning wind turbines, while others apply general recommendations. The Ministry of the Environment assessment process in Ontario is similar to other jurisdictions.

A literature review, focussed mainly on a) Metrological effects on wind turbine noise generation; b) Assessment procedures of wind turbine noise levels and their impact; c) Particular characteristics of wind farm noise; and d) Human responses to wind farm noise levels, was conducted. It showed that - local terrain conditions can influence meteorological conditions and can affect the expected noise output of the wind turbines; assessment procedures of sound power levels and propagation models, applied in different jurisdictions are quite similar in their scope; wind farm noise do not have significant low-frequency (infrasound) components; and modulations effects can impact annoyance;

The Ministry of the Environment's procedures to assess wind farm noise levels follow a simple procedure that is sound for most situations. However, additional concerns still need to be addressed in the next round of revisions to their assessment process. These revisions may need to be addressed after the results from future research provide scientifically consistent data for effects such as meteorology, human response and turbine noise source character.

1.0 INTRODUCTION

1.1 BACKGROUND

The Ministry of the Environment released a guideline document, "Interpretation for Applying MOE NPC Technical Publications to Wind Turbine Generators" in 2004. The above guidance document was to assist proponents of wind turbine installations in determining the list of necessary information to be submitted when applying for a Certificate of Approval (Air and Noise) under Section 9 of the *Environmental Protection Act*. The noise guidelines in MOE publications NPC-205/NPC-232 as well as the wind generated noise levels were applied to set the noise limits. The revisions to NPC-205/NPC-232 (in draft form) did not change the evaluation of noise limits and/or procedures applicable to wind turbines. The three Ministry documents are enclosed in Appendices A through C.

The Ministry has now decided to initiate a review of the interpretation of the above policies, due to expanding body of knowledge of the noise impacts of wind turbines. The main aim of the proposed review is to assess the appropriateness of the Ministry's approach to regulating noise impacts of wind turbines. And the Ministry, to support the proposed review, has retained Aiolos Engineering to provide acoustical technical expert advice on the recent findings about low frequency and wind profiles on wind turbine noise impacts.

The scope and requirements of the technical advice can be summarized as shown below:

(1) *Review of the 2006 doctoral dissertation by van den Berg*;
(2) *Review of*
    2.1 available noise policies and guidelines;
    2.2 Review of relevant scientific literature; and
    2.3 Review of MOE's current noise policies as applied to wind turbine and
(3) *Provide expert opinion based on the above findings;*
(4) *Participate in a focus group discussion;* and
(5) *Prepare a report that provides advice on the state of the science regarding wind turbine noise and on MOE policies and procedures that relate to wind turbine facilities.*

2.0 REVIEW OF G. P. VAN DEN BERG'S DISSERTATION

2.1 BACKGROUND

Dr. G. P. van den Berg of the University of Groningen conducted research on the noise characteristics of wind turbines, the impact of wind profiles on its propagation as well as the subjective response of sensitive receptors. The results of the above research are summarized in the 2004 Journal of Sound and Vibration article (Reference 2) with the details given in his 2006 doctoral dissertation (Reference 1).

A list of documents used for this assessment is enclosed in the reference list. *NOTE:* References 2, 3 and 4 by van den Berg presents only summary results of his research and the complete details are included in his dissertation (Reference 1). Hence, references 2, 3 and 4 will not be commented upon in this review.

The main aims of van den Berg's dissertation can be summarized as follows:

i) A group of residents complained against the perceived noise effects from a wind farm located along the border between Germany and Netherlands and were unable to obtain satisfactory resolution from the authorities and hence the university's Science Shop for Physics was retained to investigate the validity of the residents' claims;

ii) The main complaints seem to centre around perception during evening and night hours, and hence the dissertation focussed on atmospheric stability and the resulting noise effects;

iii) The main hypotheses are: a) atmospheric stability, particularly stable and very stable conditions happen mostly at night time and the hub-height wind speeds can be higher than those predicted from the 10 m high wind speeds using standard methods, such as the logarithmic profiles of the IEC standard. And hence, the wind turbine noise levels can be higher than expected. It was also conjectured that these discrepancies are prevalent during summer months; and b) beat-sounds can become very pronounced during stable and very stable conditions.

The research uses a set of measurements near one wind farm as well as wind data from locations between 10 km and 40 km from the wind farm area. The whole thrust of the dissertation is to prove the hypotheses listed above.

The dissertation is broken into ten chapters, four general sections and four appendices. The chapter titles are: I) Wind power, society and this book: an introduction; II) Acoustical practice and sound research; III) Basic Facts; IV) Loud sound in weak winds; V) The beat is getting stronger; VI) Strong winds blow upon all turbines; VII) Thinking of solutions; VIII) Rumbling sound; IX) General conclusions and X) Epilogue.

Chapter I is basically an introduction and a justification for conducting the doctoral research by van den Berg. The reasons are seen to be based on anecdotal responses rather than from a truly scientific and statistical analysis of response surveys. Chapter II is a strong criticism of acoustic consultants and their inadequate effort in finding the true wind turbine noise levels and their potential impacts.

Chapters III, IV, V and VI are the relevant chapters for this review and assessment. The assessment will be presented in subsequent sections. Chapters VII through X are not critical for the current assessment and will not be commented upon. The assessments are presented next.

2.2 CHAPTER III – BASIC FACTS

Chapter 3 contains four sections and Sections 2 and 4 provide relevant background materials. Section 2 discusses wind profiles and Section 4 presents the many sources of wind turbine sound.

2.2.1 Wind Profiles and Atmospheric Stability

The main contention of this dissertation is that the hub-height velocity can be much higher than predicted with simple formula used currently in standards and other literature. This section presents two simple velocity profile equations to obtain wind velocities at different heights (Equations III.1 and III.3). Eq. III.3 is the standard logarithmic profile used in current literature.

This equation is being questioned as to its validity by this dissertation. Equation III.1 is a simple power law relationship with a shear coefficient as the exponent. Even though the dissertation states that Eq. III.1 has no physical basis, the dissertation applies this equation with 'suitably chosen' shear coefficient 'm' throughout the dissertation. Equation III.1 has been applied in many areas of engineering application and it is based both on dimensional analysis and empirical relationship obtained from field measurements. These two equations from Reference 1 are presented here for completeness sake.

$$V_{h2} / V_{h1} = (h_2/h_1)^m \qquad \text{III.1}$$

where 'm' is the shear coefficient, h_1 and h_2 are the two heights and V are the wind velocities at heights h_1 and h_2.

$$V_{h2\,log} / V_{h1} = \log(h_2/z_0) / \log(h_1/z_0) \qquad \text{III.3}$$

where z_0 is a roughness length of the surrounding terrain.

2.2.2 Main Sources of Wind Turbine Sound

A brief summary is presented of the different mechanism of noise generation including the interaction between the mast and the blade. Considerable amount of literature is available that outlines the noise from rotating aerofoil from early 1900s onwards. Hence, the information presented is a summary of earlier research.

However, it must be pointed that the dissertation mentions and/or presents information throughout the dissertation either heuristically or by presenting only scant data. One such case can be seen in Chapter III where it is stated, "An overview of stability classes with the appropriate value of m is given in Table III.1." No documentary evidence is given for the chosen values of 'm' or how the appropriateness of 'm' was determined. The reason this point is made here is the 'stability class' designation can change drastically depending on the value of 'm'. Table III.1 of Reference 1 is reproduced below.

Table III.1: stability classes and shear exponent *m*

Pasquill class	name	comparable stability class [TA-Luft 1986]	*m*
A	very unstable	V	0.09
B	moderately unstable	IV	0.20
C	neutral	IV2	0.22
D	slightly stable	IV1	0.28
E	moderately stable	II	0.37
F	(very) stable	I	0.41

2.3 CHAPTER IV: LOUD SOUNDS IN WEAK WINDS – EFFECT OF THE WIND-PROFILE ON TURBINE SOUND LEVEL

This is one of the most important chapters in the dissertation. The main hypothesis of the chapter is to show that the hub-height velocity can be higher than predicted from the 10 m high wind speeds using standard methods during stable and very stable atmospheric conditions and hence the wind turbine noise levels can be higher than expected even though the ground level velocities can be small at 2 m and 10 m heights. Such a wind-profile is possible when the atmospheric stability class is a combination of Pasquill Classes E and F with quiet winds and no cloud cover.

Chapter IV is supposed to prove the above hypothesis with scientific support.

2.3.1 Basic Assessment

The first three sections of the chapter provide background information on the Rhede wind farm in northwest Germany that abuts Netherlands. Even though, the noise assessment showed that the wind farm complies with both German and Dutch guidelines, nearby Dutch residents complained about the noise levels. The Science Shop for Physics of the University of Groningen (van den Berg's faculty) was retained to assist the residents to resolve their concerns. Section 3 presents anecdotal responses of two residents and their perception of wind turbine noise – 'pile driving sound', 'thumping sound', 'endless train sound' and such. There is no subjective polling under a blind survey to accompany the technical data presented.

2.3.2 Sound Emission and Sound Immission Levels

Long-term noise measurements were conducted at two receptor locations near the Rhede Wind Farm at two different time periods. Location A is 400 m west of the wind farm and Location B is 1500 m west of the wind farm. Wind velocities at 2 m and 10 m heights were measured only at Location A. ***NOTE:*** *It must be pointed out that wind speeds at hub-height were not measured.* The area around Location B has both low and tall trees in its vicinity. The following explanation and we quote, "As, because of the trees, the correct (potential) wind velocity and direction could not be measured on location B, wind measurements data provided by the KNMI were used from their Nieuw Beerta site 10 km to the north. These data fitted well with the measurements on location A" was offered to justify the use of data from a far-off wind-measuring location. The above statement is heuristic at best since no data (figures and/or tables) were provided to back the above claim. Hence, it was very difficult to make sense of the data presented in the dissertation document. Similarly, meteorological data from Elde site (40 km to the west) was used to establish neutral and stable atmospheric classes for the above two sites. Even though the section states that not all Elde observations would be valid for Locations A and B, the report still used the Elde information without qualifying its validity.

The main aim of the fourth chapter was to show that the atmospheric class during night is 'stable' or 'very stable'. The stable classes, supposedly, produce hub-height wind speeds that are higher than day time values, even though the 10 m high wind speeds could be low at night and the standard wind profiles are not able to predict the high hub-wind speeds at night. The outcome of the above hypothesis is that the night time noise levels, therefore, are higher than expected. However, as shown above, the establishment of atmospheric classes itself becomes suspect. Hence, the subjective perception that the noise levels were high may be due to low ambient sound levels during the late evening and night time hours, thereby making the wind farm noise audible.

2.3.2.1 Sound Emission Levels

Sound emission levels are the sound levels generated by the wind turbines and it is crucial to extract the levels from field measurements of overall levels. The noise levels from nine turbines were measured (Section 6) and an empirical relationship between the sound power and turbine rpm was established. The resulting sound power levels were used to calculate the noise levels at receiver locations and compare them with local measurements.

2.3.2.2 Sound Immission Levels

Sound immission, a phrase used in Europe, refers to the sound levels at receptor locations. Sound immission levels at Locations A and B were discussed in Section 7 of Chapter IV of Reference 1. The data provided is very difficult to analyse and at times very confusing. 371 hours of data for Location A and 1064 hours of data for Location B were collected. Since the monitors were un-manned, the differences in A-weighted sound levels between the 5th and 95th percentiles over 5-minute intervals were used to determine the dominance of turbine sound. The report uses a value, $L_5 - L_{95} \leq 4$ dBA, to deduce (Figure IV.4 of Reference 1) the duration of high sound levels at night time and at day time. There was no reason given as to the selection of the 4 dBA number. One would have expected a lower value, if the wind turbines were the main dominant noise sources. Actually, the value was close to 3 dB as described in Chapter V of Reference 1 (page 71 – $R_{bb,90}$ at Location P was around 3 dB). Figure IV.4 is reproduced below.

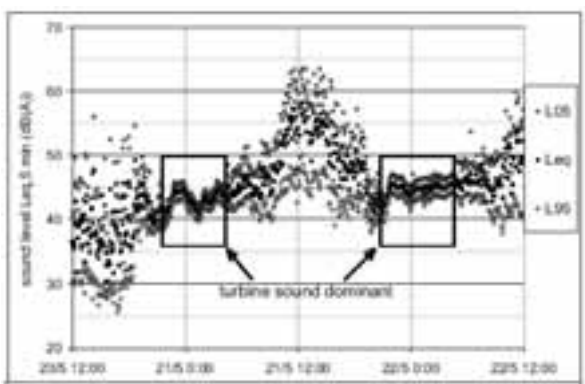


Figure IV.4: 48 hour registration of immission level (L_5, L_{eq} and L_{95}) per 5 minutes at location A; turbines are considered the dominant sound source if L_5-L_{95} ≤ 4 dB

The criterion of $L_5 - L_{95} \leq 4$ dBA to determine the dominance of wind turbine noise is critical to the assessment. If the sound was steady during the 5-minute period, the above difference would be zero. Since outdoor sound levels are never steady, one would expect some variability. However, it is our belief that 4 dBA range is too high. If one were to reduce the difference to 2 dBA or 3 dBA, the night time duration for dominant sound levels would reduce substantially compared to the results presented in Table IV.3 of Reference 1. Table IV.3 is reproduced below.

Table IV.3: total measurement time in hours and selected time with dominant wind turbine sound

Location	total time (hours and % of total measurement time at location)	Night 23:00-6:00	Evening 19:00-23:00	Day 6:00-19:00
A: total	371 h	105	75	191
A: selected	92 h 25%	76 72%	9 12%	7 4%
B: total	1064 h	312	183	569
B: selected	136 h 13%	119 38%	13 7%	4 0,7%

The sound immission levels from all the measurements (the entire 1435 hours of data) were organized into the dominant turbine noise levels based on the 4 dBA difference and presented in Figure IV.5 of Reference 1, which is reproduced below. This figure with four sub-plots, is the most difficult figure to decipher. This is one of the most important figures used to conclusively provide evidence for the main argument of the dissertation. If one does not accept the 4dBA argument, the whole data structure of Figure IV.5 of Reference 1 is suspect. Further to cloud the issue, stable and neutral atmospheric classes, gleaned from Elde data (located 40 kms away) was superimposed. [Reference 1 on Page 47 does state that not all Elde data would be valid for Locations A and B, but continues, anyway, to use the invalid data to determine stability classes]. One must also infer that 'stable' classes occur only at night time and 'neutral' classes occur during the day time, even though the above was not stated explicitly in the report. No proper explanation was given for applying the above inference.

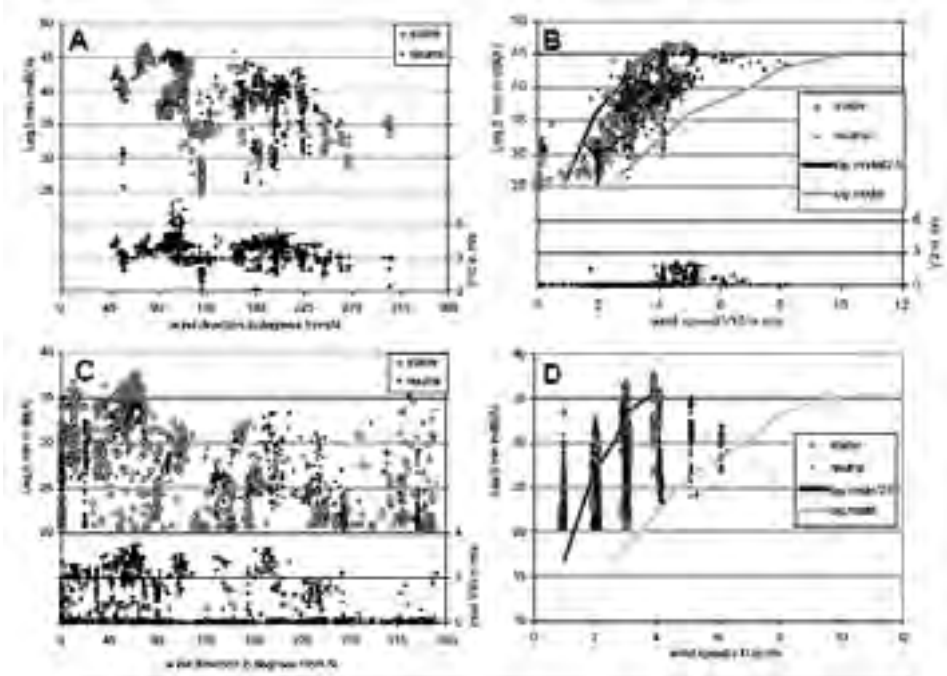


Figure IV. 5. measured sound levels $L_{eq,5\ min}$ at locations A (above) and B (below) as a function of median wind direction (left) and average wind speed (right) at reference height (10 m), separated in classes where the atmosphere at Eelde was observed as stable (open diamonds) or neutral (black dots). Also plotted are expected sound levels according to logarithmic wind profile and wind speed at reference height (grey lines in B and D), and at a 2.6 times higher wind speed (black lines in B and D). Figures A, B and C also contain the wind speed $v_{10}(A)$, $v_2(B)$, and the local $v_{10}(C)$ disturbed by trees, respectively.

Figures IV.5 B and IV.5D Reference 1 present the variation of 'dominant' turbine noise levels as a function of wind speed measured at a height of 10 m. **NOTE:** It must be pointed out that no wind speeds were measured for Location B. The data points ($L_{eq,\ 5\ min}$ in dBA) were also separated into 'stable' and 'neutral' atmospheric classes. In addition, the calculated sound levels from the sound power data from Section IV.6 were also plotted in these two figures. The wind speed at 10 m height for the calculated plot was evaluated using the logarithmic wind profile of Equation III.3 shown in Section 3 of the current assessment report. Since the logarithmic wind profile was supposed to be incorrect, a corrected noise level plot, by applying a factor of 2.6, was also included in Figures IV.5B and IV.5D of Reference 1. These two figures were used to make two strong statements against the procedures used to assess wind-turbine and wind farm noise impacts.

Statement I: 'Stable' atmospheric conditions occur at night time and wind turbine noise levels are higher than expected due to high wind-velocities at hub-height.

Statement II: Logarithmic wind profile, generally used in standard procedures, is incapable of predicting current wind speeds at various heights for 'Stable' atmospheric classes, occurring at night time. And hence, these higher than expected noise levels occur at night time with low ground wind speeds, thereby, increasing the impact on residents.

However, the two figures do not provide conclusive evidence to support the above two statements for the following reasons. Contrary evidence to Statement I will be further discussed in the next section with field data from New Zealand and Australia.

a) The 'stable' and 'neutral' class designations used in the two figures are applied from a location 40 kms away and hence not valid for Locations A and B;
b) Both classes seem to produce high as well as low sound levels as clearly seen for Location B (Figure IV.5D Reference 1);
c) The light grey sound level line supposed to represent the 'neutral' class quite accurately (as stated in Chapter III of the dissertation). If that were to be true, all of the 'neutral' class data points would have collapsed near that line. However, that was not the case, as the data points are scattered all over the figures;
d) Even at a distance of 400 m from the wind farm (Location A), only a small percentage of the 'neutral' class noise levels is near the neutral line;
e) Finally, if the $L_5 - L_{95}$ value is close to 2 or 3 dBA, the entire dominant sound levels at night time could occur well below the 25% to 35% time presented in this dissertation.

As part of the current investigation Aiolos Engineering undertook a brief review of summer weather data near a wind farm located adjacent to Lake Huron in Southern Ontario. Summer data was reviewed as the main hypothesis of van den Berg is that the wind speed discrepancies due to stability classes are severe during the evening and night hours of summer months. The

objective of this review was to test the rigour of the two "van den Berg" Statements I and II. Since this review was conducted in the context of the current investigation and this report, the scope of the review was limited both in its duration and site selection. The review of this data will show that limited data of the type that van den Berg relied on cannot be used to draw strong conclusions.

Aiolos Engineering compiled wind speed data from one weather station in Ontario for a period of three summer months (June, July and August 2006). The Environment Canada's weather station at Goderich, Ontario is situated within a few kms of a wind farm with 21 wind turbines. The Kingsbridge wind farm has the capacity to generate 40 MW of power. The data for the three month period was compiled in different formats and the results are presented in Appendix D. The atmospheric stability classes were approximated using the information from the AIR-EIA website (Reference 19). Even a cursory perusal of the Appendix D data would show that the correlation between stability classes and power generation is quite inconsistent. The power generated by the wind farm was obtained from the Independent Electricity System Operator's data base for Ontario (Reference 34). Unless a detailed study of the wind power generation and wind speed behaviour at the wind farm location is conducted, one cannot make strong conclusions as presented by van den Berg's work. Another salient observation from Appendix D data is that the wind farm power generation and wind speed behaviour is highly localised, controlled by the local conditions

One must point out at this juncture, that the conjectures presented in van den Berg's Statements I and II may well be true. However, the research presented in van den Berg's dissertation has not provided strong scientific evidence for the same. In addition, the data of figures IV.5 clearly shows that the sound levels at Location A, 400 m west of the wind farm is less than 40 dBA and the noise levels at Location B, 1500 m west of the wind farm, is less than 35 dBA for a substantial portion of the measurement period.

2.4 CHAPTER V: THE BEAT IS GETTING STRONGER – LOW FREQUENCY MODULATED WIND TURBINE SOUND.

Chapter V deals with the effect of frequency modulation of the wind turbine noise levels. This chapter is an important chapter since it is supposed to provide evidence that the beating phenomena gets stronger with worst results during the 'stable' atmospheric classes. The 'stable' atmospheric classes are supposed to occur only during late evening and night time hours and the turbine is supposed to generate higher than expected noise levels with the ambient sound levels at the receivers being low due to lower than expected ground speeds. The inference here, therefore, is that any modulation of higher noise levels would cause additional hardships on the receiver. This chapter aims to show that the above is true.

Chapter V is broken into 3 main sections. Section V.1 discusses the effects of atmospheric stability on wind turbine noise generation. It discusses, three possible effects, purely as theoretical conjunctures that beating (or modulation) can be due to - a) the increase in the angle of attack changes between the blade at its highest location and at its lowest location during stable conditions; or b) increase in the wind direction gradient between the blade at its highest location and at its lowest location during stable conditions; or c) reduced wind turbulence during stable conditions. No supporting experimental evidence was forthcoming. We agree that purely from theoretical consideration that the three possible mechanisms can produce amplitude modulation phenomena. But, does this happen only for 'stable' and 'very stable' atmospheric conditions and only at night time?

The other major misconception arising out of this chapter is the terms used to describe the said phenomenon – 'swishing', 'thumping', and 'beating'. The beating phenomenon in acoustics called *beat* is a special event when two sounds occur with their dominant frequencies very close to each other. A general description of *beating* is presented in Appendix E. The amplitude modulation phenomenon is different from *beating*. The acoustical principles that describe the amplitude modulation phenomenon are generally considered to be related to the movement of the turbine blades through air and the interaction of the blades with the stationary mast. In addition, the amplitude modulation could be caused by the nature of wind itself – random both in speed

and direction. Irrespective of the underlying principles, the amplitude modulation produced by wind turbines is a different phenomenon from acoustical *beating.*

The UK working group on Wind Farm noise (Reference 30) studied the phenomenon of amplitude modulation and found the levels inside residential bedrooms to be below the sleep disturbance level. Importantly, the UK report recommended that further studies be conducted to understand the amplitude modulation better. [Further descriptions of the aerodynamic modulation will be presented in Section 4].

Section V.2 presents measurement at three locations; two near the Rhede wind farm and the third location (Location Z) is near a single small wind turbine. Between 10 and 15 minutes of data were collected. The measurement results are presented in terms of spectral variations. The wind velocity was measured only near one location and the wind speed data for Location Z was obtained from a number of nearby weather stations. Two conclusions were obvious from the results:

a) the infra-sound, when measured as dBG with the G-weighting scale, was found to be not audible, approximately between 15 – 20 dB below the threshold of perception, indicating that modern wind farms do not generate infrasound levels that are perceptible. For information on G-weighting network, please see Reference 31;
b) the A-weighted sound levels correlated with spectra around 400 Hz which indicates the major source is the trailing edge noise.

The main thrust of this chapter was to discuss the amplitude modulation phenomena. The modulation at Location P was audible during the measurements period, but very small at Locations R and Z. The main effect of the modulation is not to produce low frequency sounds, but change the amplitudes which are discernable by the receivers. The results showed amplitude modulation at Location P with a variation of about 5 dBA between maximum and minimum. Even though the measurements were conducted for a long duration, only 180 second of measured data was shown to prove the existence of the modulation (beating) in Figure V.4 of

Reference 1. The modulation was seen to be strong only for 30 seconds. Even though the variation was 1 dB more at Location R, no modulation was discernable. No explanation was given for these discrepancies. Even though the level variation did not indicate beating at Location R, the level variations for Locations A and B from Chapter IV were shown in Figure V.7 of Reference 1 to conjecture that modulation would happen at these locations, 28% of the time and 18% of the time respectively. Since the measurements at Locations R, P and Z were conducted at early morning hours (midnight), it was assumed to be stable weather conditions. No data was provided to substantiate the absence of modulation during other weather conditions, such as 'neutral' and/or 'unstable' atmospheric classes. Hence, one cannot immediately conclude that modulation occurs only during the 'stable' and 'very stable' atmospheric class. Figures V.4 and V.7 of Reference 1 are reproduced below,

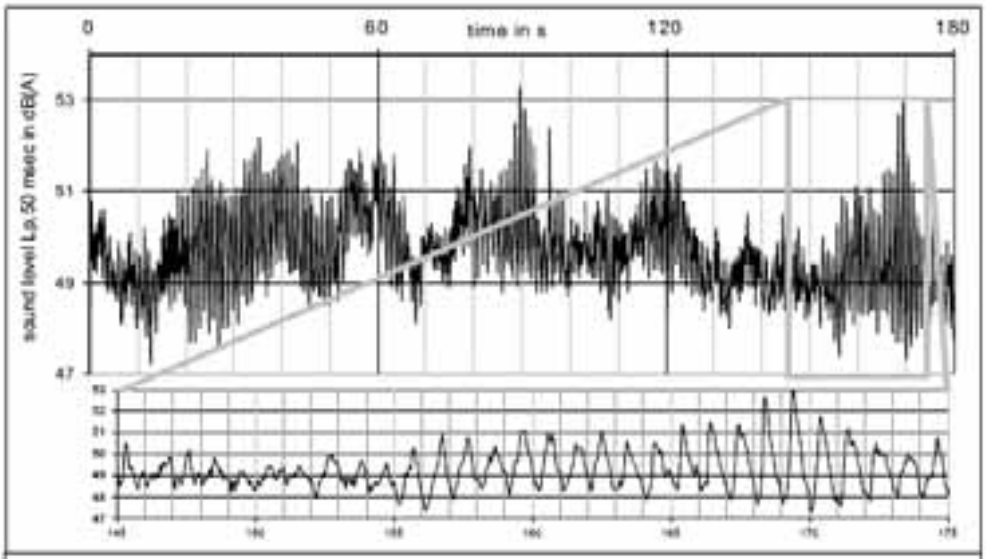


Figure V.4: fluctuations in broad band A-weighted sound immission level at façade of dwelling P; the lower panel is an expansion of the part within the grey rectangle

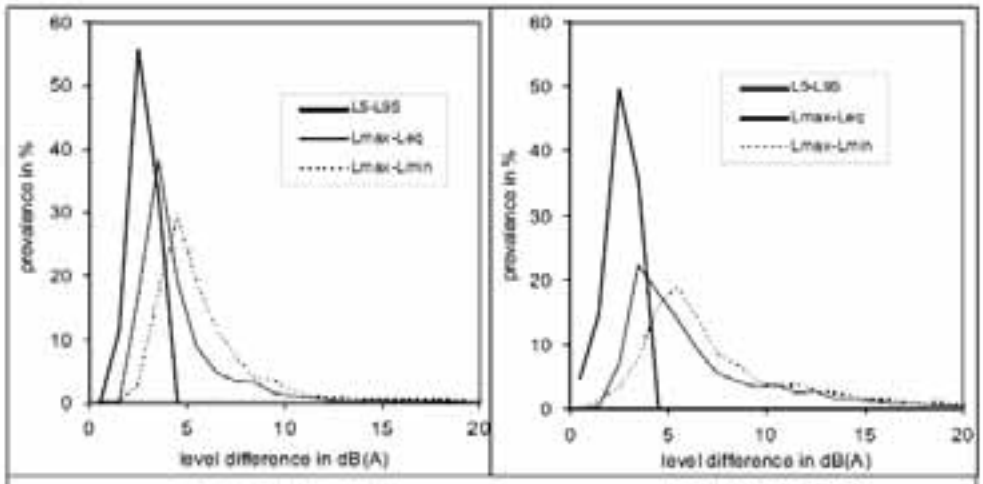


Figure V.7: statistical distribution of level differences (in 1 dB-classes) between high and low sound levels within 5 minute periods at 400 m (left) and 1500 m (right) from the nearest wind turbine

Finally, Section V.3 discusses the perception of the modulated sound. It begins by quoting the subjective response work of Pedersen and Waye (Reference 5) that about 20% of residents would be annoyed with noise levels in the range of 37.5 dBA to 40 dBA. It then jumps to anecdotal responses of two residents near the Rhede farm. There are no studies cited in van den Berg's work that show a correlation between modulated sound and annoyance and hence van den Berg conjectures the annoyance would be worse since the expected amplitude variations make the perception of the sound strong. However, no evidence other than anecdotal responses was forthcoming.

2.5 CHAPTER VI: STRONG WINDS BLOW UPON TALL TURBINES – WIND STATISTICS BELOW 200 M ALTITUDE

This chapter deals with actual wind speed data from one site in western part of the Netherlands. The wind velocities at different heights, 10 m, 20 m, 40 m, 80 m, 140 m and 200 m were measured at half-hour intervals. The results, averaged for the entire year showed that higher wind velocities compared to the predicted wind speeds from the 10 m high wind velocity, indicating a stable atmosphere. Even the daily variations over seven days in summer months are small during the night time hours (Figure VI.3 of Reference 1, reproduced below).

The data described in Section 2.3.2.2 and presented in Appendix D was further analysed to look at the daily variations in wind speeds. In addition to Goderich weather station, the data from a few more weather stations located within 30 km radius of existing wind farms were compiled by Aiolos Engineering. Figures 2.1 thru' 2.6 show results of one-hour averaged wind speeds from three weather stations near three wind farm sites in southern Ontario. The weather data was collected at a height of 10 m above ground. The daily variations for a few summer days shown in Figures 2.1, through 2.6 seen to indicate substantial variations in wind speeds from day to day. As was explained in Section 2.3, summer data was reviewed as the main hypothesis of van den Berg is that the wind speed discrepancies due to stability classes are severe during the evening and night hours of summer months.

The measurement results of Botha [Reference 22] for four sites in New Zealand and Australia showed contradictory results of wind speed gradient. They will be discussed in Section 4. Hence, the main conclusion here is that the data presented in Chapter VI of Reference 1 is valid only for that one site in Netherlands.

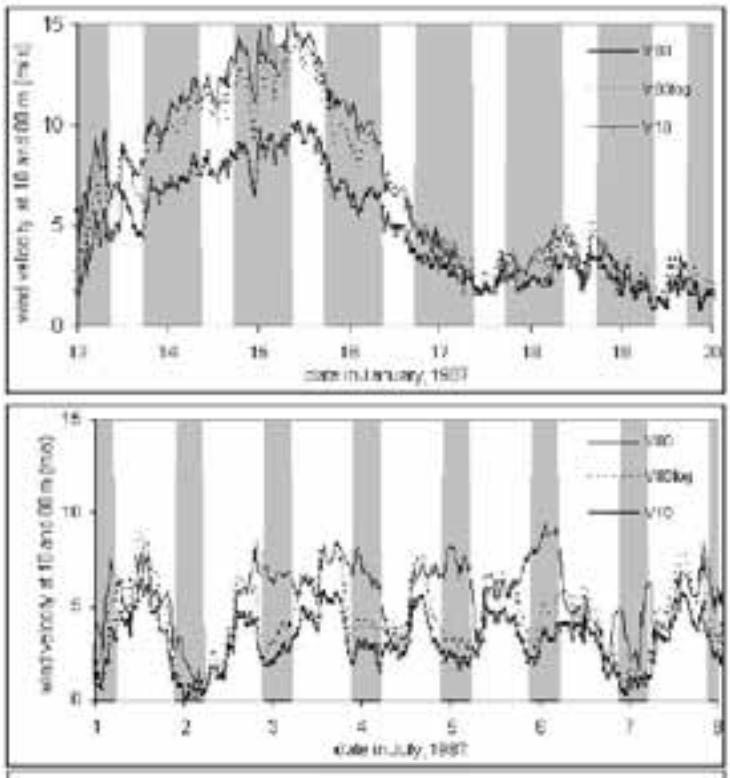


Figure VI.3: wind velocity at 10 and 80 m (solid lines), and logarithmically extrapolated V_{80log} (dotted line) over 7 days in January (top) and July (bottom); grey background: time when sun is down

The chapter then calculates expected power production at these velocities as well as calculates noise levels from the wind farm. The results show that the discrepancy for the Cabauw site between stable noise and standard logarithmic wind profiles is of the order of 2 dB. These differences are averaged from one site. The main drawback of the results of this chapter is that they are not transferable to every wind farm site in the world.

One must point out that it may be possible that during summer months stable and very stable conditions may exist at night time producing higher than expected noise levels and hence increasing the impact. However, the data presented so far does not lead one directly to that conjecture.

Figure 2.1 Elora Wind speeds

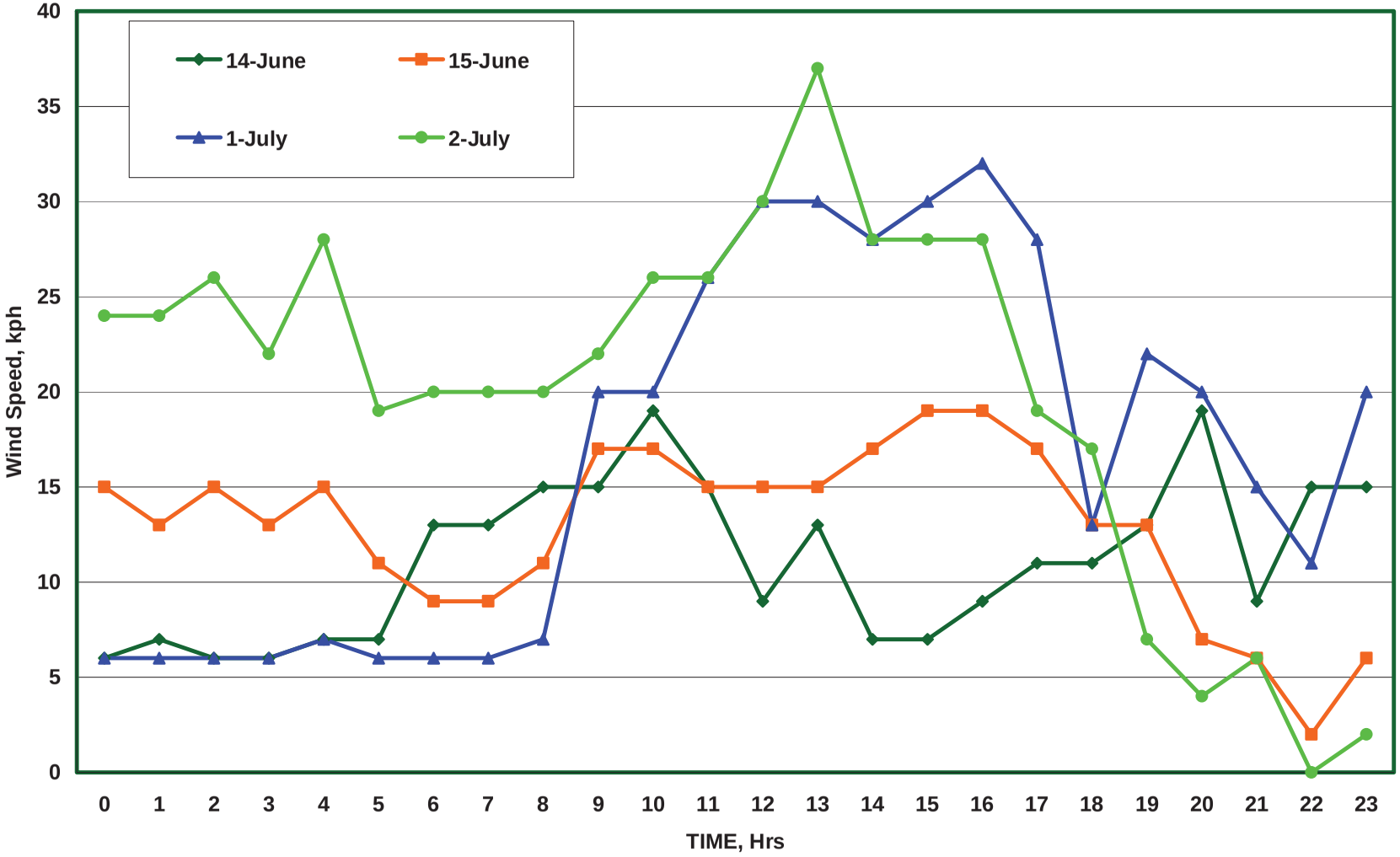


Figure 2.2 Elora Wind speeds - 2.

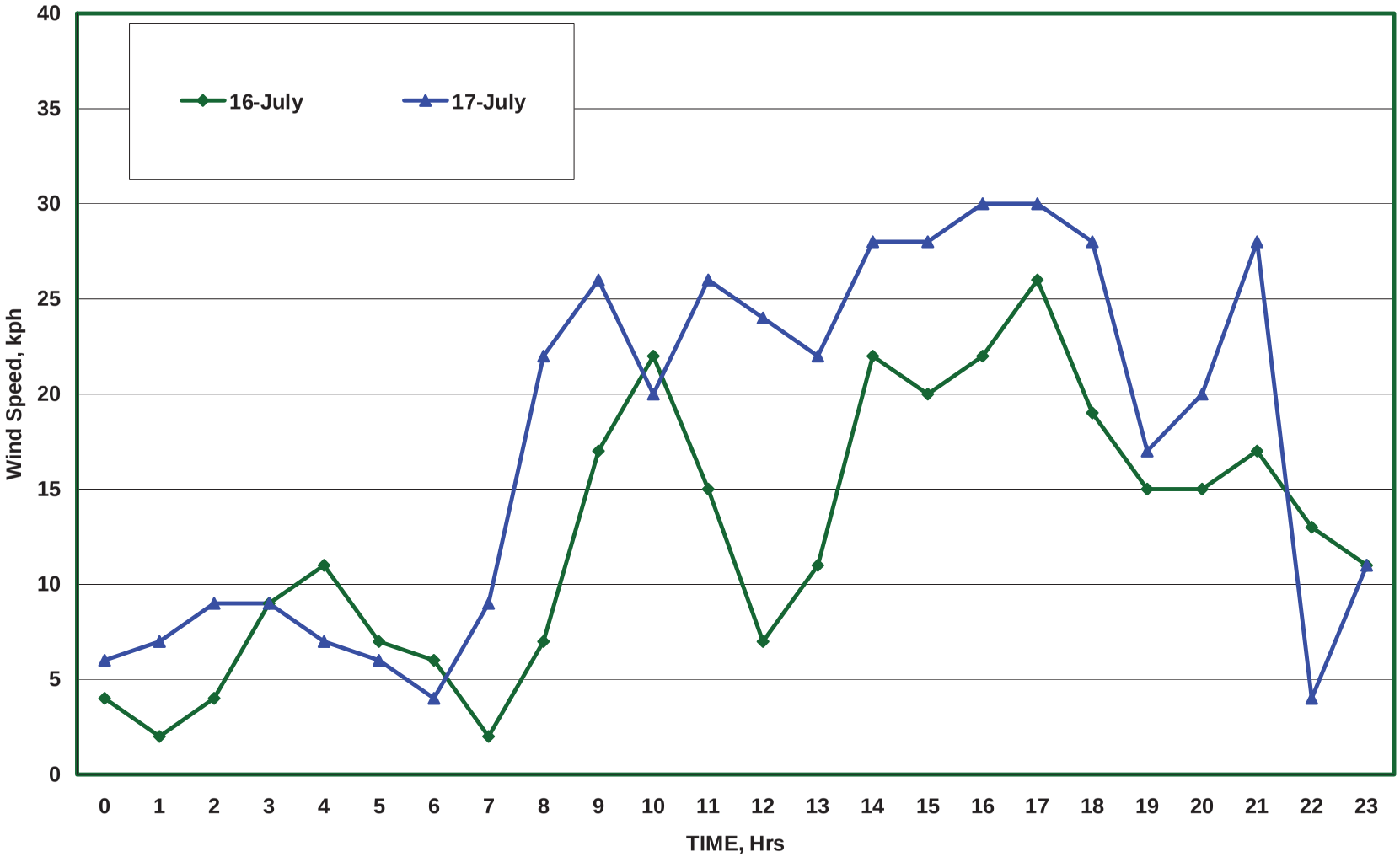


Figure 2.3 Goderich Wind speeds

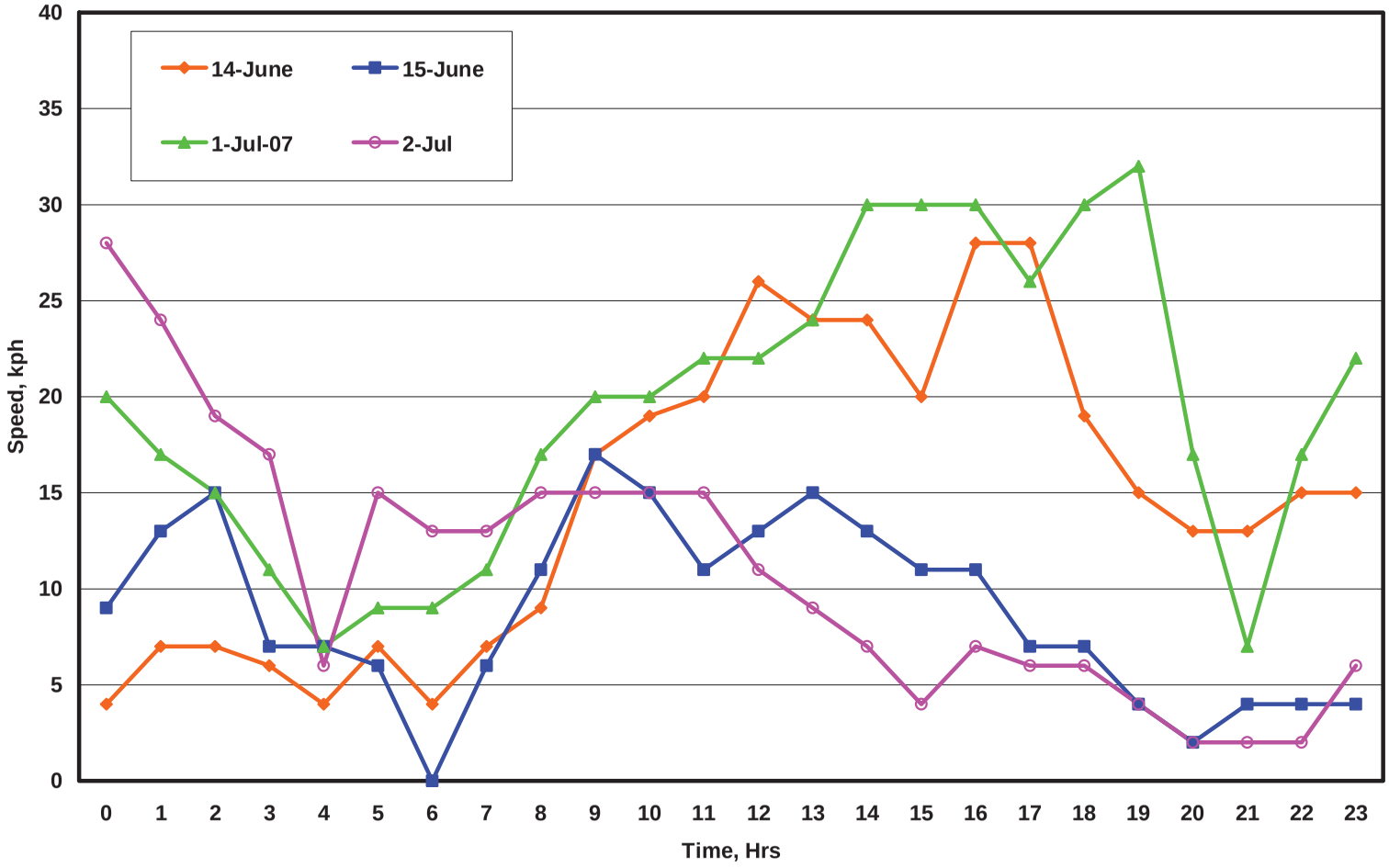


Figure 2.4 Goderich Wind speeds - 2

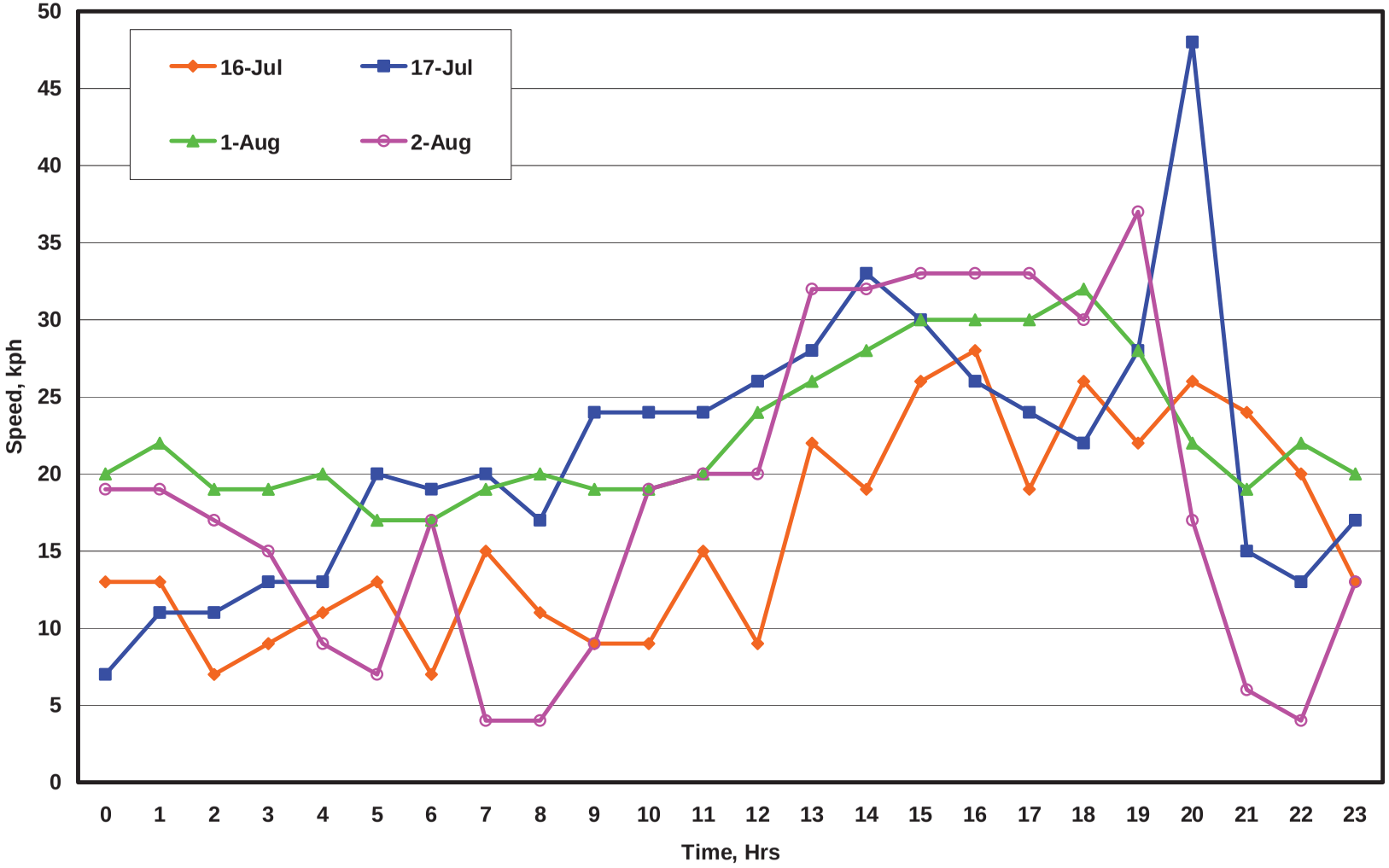


Figure 2.5 Elora and Goderich Wind speeds.

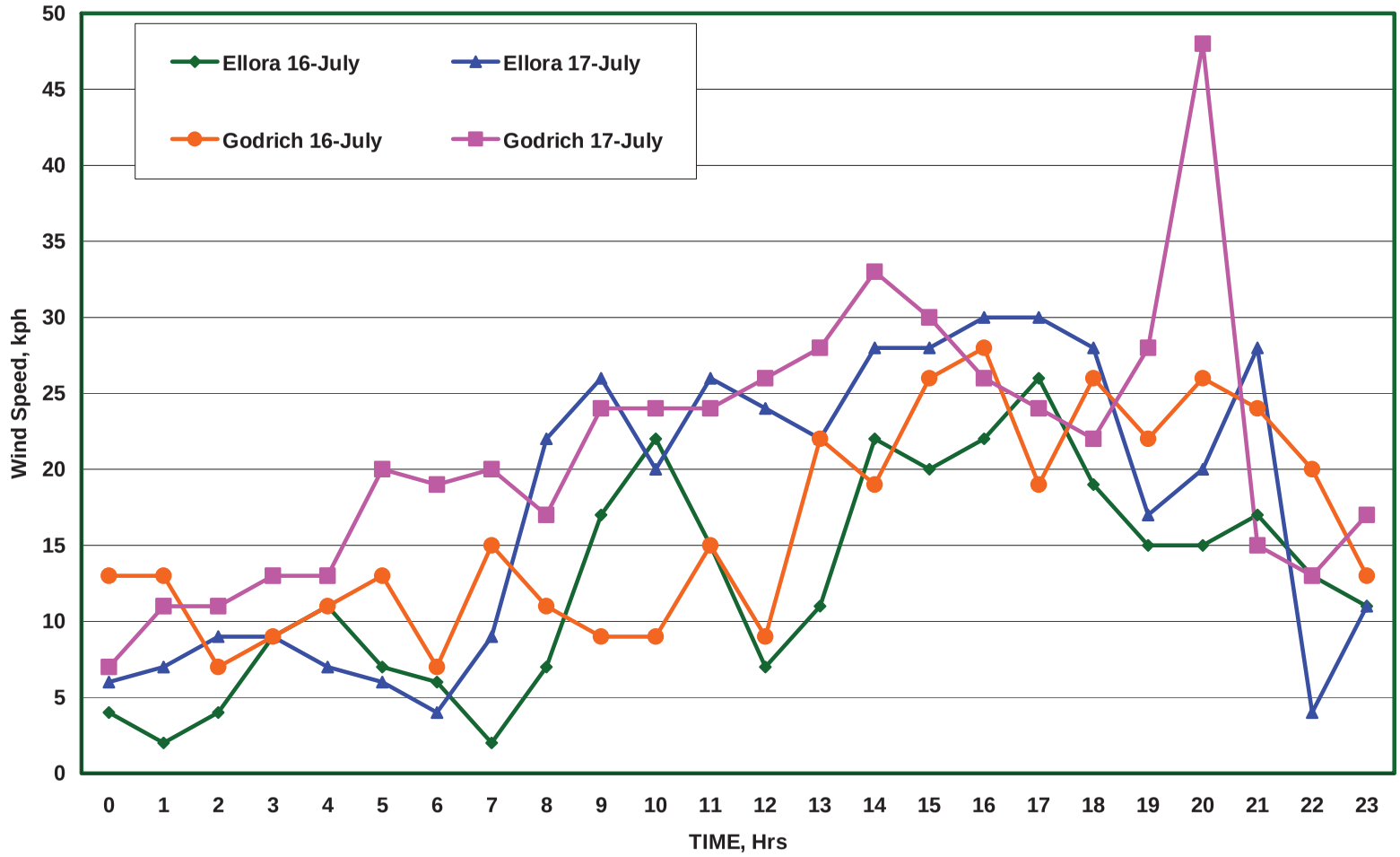
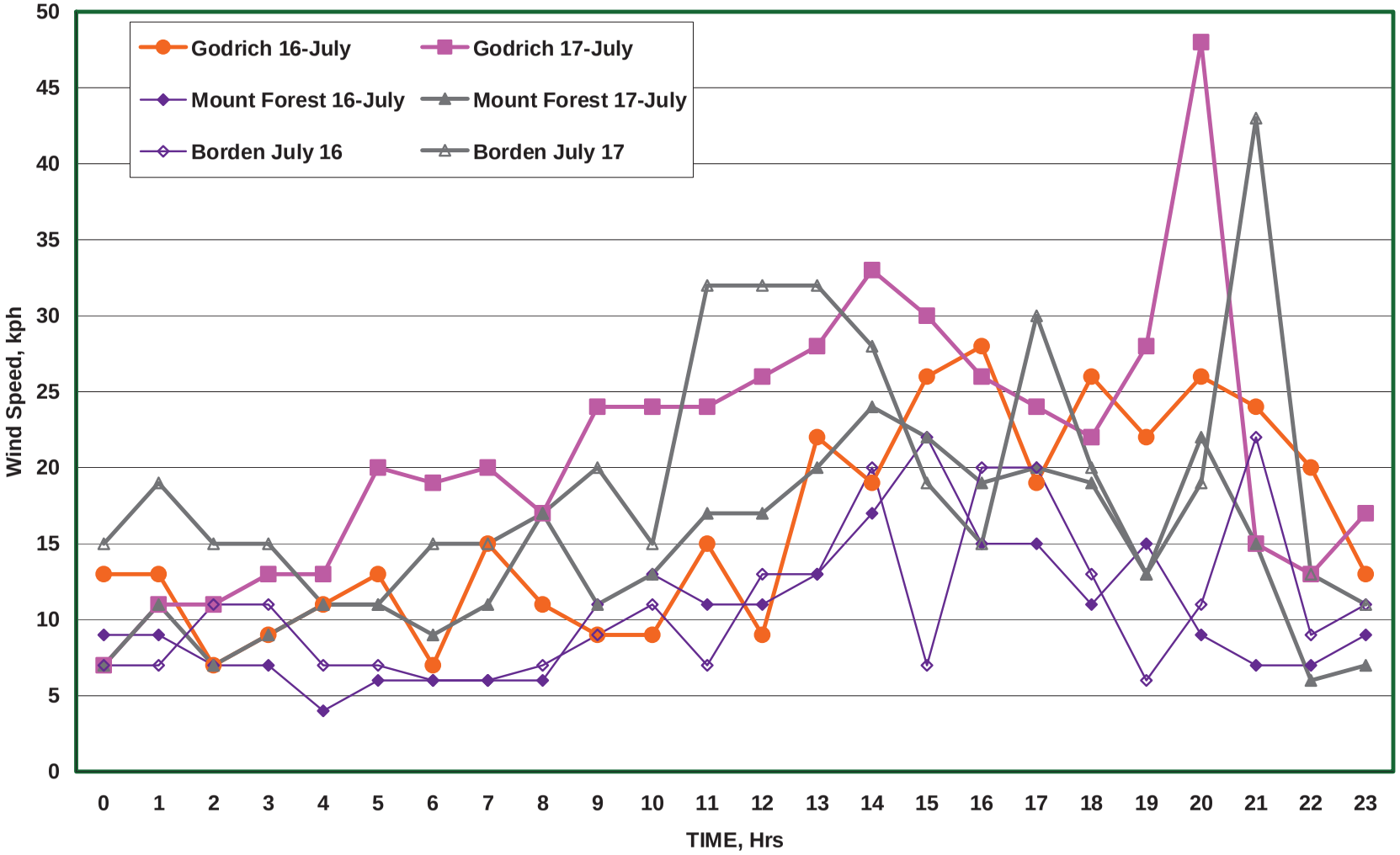


Figure 2.6 Borden, Mount Forest and Goderich Wind speeds.



2.6 SUMMARY

The doctoral dissertation of G. P. van den Berg was reviewed and comments were provided in this section. The dissertation was to provide scientific evidence for increased annoyance from wind farm during evening and night time hours. The review showed the above was not the case and the review comments are summarized below.

One of the main criticisms of the doctoral dissertation of van den Berg is that the conjectures of his research have not been supported by solid scientific data.

The major deficiencies of the doctoral dissertation are highlighted below:

A) Simultaneous noise measurements and subjective response from a random sample of the residents were not performed other than a few anecdotal responses;

B) The wind velocities at various heights were not conducted either at the turbines or near them to evaluate the atmospheric classes, but applied weather data from a location 40 kms away;

C) The wind farm noise levels at receptors were unmanned and the procedure to evaluate the dominance of turbine noise may not be correct.

D) The immission levels measured at 400 m and 1500 m distances had a large scatter to provide strong conclusions. **NOTE:** It must be pointed out that the receptor noise levels, for a substantial portion of the measurement period, were less than 40 dBA at a location 400 m away and less than 35 dBA at a location 1500 m away.

E) The *beat* of acoustics is being identified, wrongfully, with amplitude modulations and no strong evidence was provided to show the modulation gets worse at night compared to day time in the summer.

Despite the rather strong conclusions of Reference 1 some of the basic conjectures in the dissertation merit further examination. Hence, the research of van den Berg may be considered as the catalyst that started serious discussion on many aspects of wind farm noise. Future research must therefore provide stronger scientific data to validate these different noise concerns.

3.0 REVIEW OF AVAILABLE NOISE POLICIES AND GUIDELINES

The second task for the current project was to provide an evaluation of the noise policies on Wind Turbine noise applied in jurisdictions other than the Province of Ontario.

The noise policies from different Canadian provinces, USA states and a few other countries were reviewed. The regulations from Germany and the Netherlands were gathered from other review papers. [See for example Reference 18].

General comparison of the noise regulations is presented in Table 3.1.

3.1 WHO GUIDELINES FOR COMMUNITY NOISE
(Reference R1)

The community noise guidelines are the result of significant amounts of research in the relationship between noise and health. There is an understanding that noise pollution can be the cause of serious health effects through short term and long term, or cumulative, exposure. The guidelines include the values of what the World Health Organization feels to be the thresholds to health effects in various situations. The limit that has been listed in an outdoor living area, such as around a dwelling, is 50 dBA for moderate annoyance. Once the sound level has increased to 55 dBA, it is considered to be a serious annoyance. For indoors, the World Health Organization recommends the noise level to stay below 35 dBA before moderate annoyance occurs, and below 30dBA to avoid sleep disturbance at nighttime. For conditions at nighttime with an open window, the suggested limit is 45 dBA to avoid sleep disturbance. Many of the documents below reference these guidelines in the justification of selecting certain noise limits, although the Ontario Ministry of the Environment publication does not. They are also widely referred to in other literature relating to noise level limits.

Table 3.1 Comparison of Noise Regulations.

Jurisdiction	Daytime Limit	Nighttime Limit	Background SPL Establishment	Wind Turbine SPL Establishment	Minimum Setback	How Impact is Assessed
ONTARIO	Whichever is greatest: - Urban Areas, wind speeds below 8m/s: 45 dBA or hourly background level - Rural Areas, wind speeds below 6m/s: 40 dBA or hourly background level - Wind speeds above 8 and 6 m/s each type: wind induced background level LA_{90} plus 7dBA or hourly background level		NPC-205 or NPC-232 whichever is higher	IEC 61400-11, to be provided by manufacturer	N/A	Impact Assessment to ISO 9613 method to be submitted prior to approval for critical points of reception up to 1000 m.
Alberta	Nighttime + 10 dBA	40 dBA – 56 dBA minimum	Pre-assumed based on proximity to transportation and number of dwellings OR 24 hours, 10 min. intervals in special cases	Modeling at wind speeds of 6 to 9 m/s to achieve worst-case scenario	N/A	Noise Impact Assessment Required to be submitted for application – form given in document Noise measurements, including CSLs *recommended* for speeds 4 to 6 m/s between 1.2 and 10 m above grade
British Columbia	40 dBA at residential property		N/A	Modeling of 8-10m/s wind speeds at 10m height to be provided by manufacturer	Siting to conform to ISO 9613-2	Risk assessment required if the difference between modeled SPL and acceptable limit is close -Measurements made if complaint is filed

Jurisdiction	Daytime Limit	Nighttime Limit	Background SPL Establishment	Wind Turbine SPL Establishment	Minimum Setback	How Impact is Assessed
Quebec	Sensitive Land: Type I = 45 dBA Type II = 50 dBA Type III = 55 dBA Non Sensitive Land: Type IV = 70 dBA Dwelling on Industrial Land: 55 dBA	Sensitive Land: Type I = 40 dBA Type II = 45 dBA Type III = 50 dBA Non Sensitive Land: Type IV = 70 dBA Dwelling on Industrial Land: 50 dBA	Length of time to current practiced standards – not specified. Measurements to fully cover reference intervals favoured	N/A	N/A	Measurements taken post-construction to ensure conformity, assess impact
New York (Town of Clinton)	50 dBA or Ambient + 5 dBA		Highest whole number in dBA exceeded for more than 5min per hour (requires independent certification)	IEC 61400-11 or other accepted procedures	- 500 ft from property line or road - 1200 ft from nearest off-site residence - 2500 ft from a school, hospital or nursing facility	Independent certification required before and after construction that noise limits are met.
Maine	Residential: 60dBA Comm/Ind.: 70 dBA Rural: 55 dBA	Residential: 50dBA Comm/Ind.: 60 dBA Rural: 45 dBA	Estimation based on population within 3000m radius or measurements during all hours the development will operate	N/A	N/A	Post-development one-hour equivalent measurements to be made
Pennsylvania	Fifty (55) dBA (note: this is what is in the document, not a typo here)		N/A	AWEA Standard 2.1 - 1989	1.1 x turbine height (consenting) or 5 x hub height (non-consenting)	N/A
Washington	Residential: 60 dBA Commercial: 65 dBA Industrial: 70 dBA	Residential: 50 dBA Commercial: 55 dBA Industrial: 60 dBA	N/A (Environmental noise measurement procedure is reserved)	N/A	N/A	Noise measurement only made if a complaint is filed

Jurisdiction	Daytime Limit	Nighttime Limit	Background SPL Establishment	Wind Turbine SPL Establishment	Minimum Setback	How Impact is Assessed
Oregon	Ambient + 10 dBA		26 dBA assumed	IEC 61400-11	350m minimum, or 1000m non-consenting	
Michigan	55 dBA or L_{90} + 5 dBA		55 dBA assumed, not indicated for higher levels	IEC 61400, ISO 9613 (modeling)	1.5 x height of tower including blade in top position	ANSI S12.18 (post construction), ISO 9613 model
Australia	35 dBA or $L_{A90, 10}$ + 5 dBA		Minimum of 2000 data points of background noise and wind speed pairs with a best fit curve	IEC 61400-11, must be overlaid on graph of background sound levels	N/A	Demonstration of compliance at all relevant receivers, if compliance is not demonstrated, operation will be restricted
New Zealand	40 dBA or L_{95} + 5 dBA		NZS 6801 (10-14 days of continuous monitoring)	Obtained from Manufacturer	N/A	Measurements taken if necessary, to follow same procedure as background levels
UK (Britain)	$L_{90, 10min}$ + 5 dBA OR 45dBA OR 35-40 dBA	43 dBA or 45 dBA	Minimum 7 days continuous 10 min interval monitoring	IEA Recommended Practice – using 8m/s at 10m height	N/A	Measurements made if complaint filed; no formal impact assessment required
Ireland	45 dBA or L_{90} + 5 dBA OR 35-40 dBA if L_{90}<35 dBA,	43 dBA	10 minute intervals	N/A	N/A	N/A

Jurisdiction	Daytime Limit	Nighttime Limit	Background SPL Establishment	Wind Turbine SPL Establishment	Minimum Setback	How Impact is Assessed
Denmark	45 dBA in open areas 40 dBA near residential		Annex 1 of the document; requires regression analysis of min. of 10 L_{Aeq} values measured for at least one minute each over different wind speeds	EN 45000 standards or min. of 10 L_{Aeq} values measured for at least one minute each over different wind speeds – see Annex 1 of document for full procedure	N/A	- Calculations of noise level at nearest property - Measurements after operation has begun or when deemed necessary, but not more than once per year
Germany	55 dBA/50 dBA in residential areas and 45 dBA in areas with hospitals, health resorts etc.	40 dBA/35 dBA in residential areas and 35 dBA in areas with hospitals, health resorts etc.	N/A	Recommended Practice – using 10 m/s at 10m height	-	- Calculations of noise level at nearest property, using DIN ISO 9613-2.
Netherlands	50 dBA	40 dBA (night) 45 dBA (evening)	N/A	-	-	-

3.2 NORTH AMERICAN NOISE LEVEL LIMITS AS APPLIED TO WIND TURBINES

The situation in North America in terms of noise level limits for wind turbines is currently under development. Many jurisdictions are only beginning to draft standards specifically for wind turbines, and few have gone beyond the draft stage. This is true for both the United States and Canada, where wind is still a relatively under-utilized energy source. There are a number of examples of noise level limits below from the Northern U.S. States, and some Canadian provinces, and they represent the variability from one jurisdiction to the next.

3.2.1 Ontario - Interpretation for Applying MOE NPC Technical Publications to Wind Turbine Generators

(Reference R2)

The Ontario Ministry of the Environment has produced a document listing noise requirements for wind turbines. The document segregates development into three separate classes, the first two referring to urban environments, and the third referring to a rural environment. The sound level limits are dependent not only on their classification, but on the wind speed also. Where wind speeds are lower than 8 m/s in an urban environment, the hourly equivalent sound level from the wind turbine facility must not exceed 45 dBA or the hourly background sound level, whichever is greater. Similarly, in a rural environment where wind speed is less than 6 m/s, the hourly equivalent sound level must not exceed the greater of 40 dBA or the hourly background sound level. In the cases where the wind speeds exceed these levels, rather than a fixed limit, the sound level is permitted to be the wind induced background sound level, L_{A90}, plus 7 dBA. This is demonstrated in the Table 3.2 below.

Table 3.2. Ontario Noise Assessment Limits

Wind Speed (m/s)	4	5	6	7	8	9	10	11
Wind Turbine Noise Criterion NPC-232 (dBA) (Rural)	40	40	40	43	45	49	51	53
Wind Turbine Noise Criterion NPC-205 (dBA) - (Urban)	45	45	45	45	45	49	51	53

The noise limits apply to both daytime and nighttime periods, with the level being measured at the nearest point of reception: a location within 30 m of an existing or zoned for future dwelling. After a distance of 1000 m between the wind turbine facility and the point of reception, a detailed noise assessment is not required.

3.2.2 Alberta - EUB Directive 038 Noise Control
(Reference R3)

Of all the documents reviewed, the sound level limits for wind farms are perhaps the most complicated to determine in the province of Alberta, Canada. Primarily, the permissible sound level, PSL, depends on the location of the nearest residences. If there are no dwellings within 1.5 km, the limit is a fixed 40 dBA (this corresponds to an increase over the assumed ambient sound level of 35 dBA in rural areas). However, if there are places of residence, the PSL must be determined by the flowing equation:

$$\text{PSL} = \text{Basic Sound Level} + \text{Daytime Adjustment} + \text{Class A Adjustment} + \text{Class B Adjustment}$$

The Basic sound level is the main component of the sound level limit and ranges from 40 dBA to 56 dBA, depending on the receiving property, and is selected from a table. The daytime adjustment allows the addition of 10 dBA to the PSL during the time period of 7 a.m. – 10 p.m. The other adjustments, Class A and Class B, require technical verification to be applied, and are only done so in specific circumstances. In order to properly determine the ambient noise level and the wind farm development's noise emissions, certain procedures must be followed which are documented in the directive. For example, the ambient sound level measurement requires continuous monitoring over a 24-hour period, 15m away from the nearest dwelling. The environmental conditions at the time of the measurements are also strictly detailed. Although their sound level limits are higher than the MOE limits, similar documentation is required, such as a noise impact assessment.

3.2.3 British Columbia - Land Use Operational Policy: Wind Power Projects (Reference R4)

The British Columbia policy regulating noise from wind turbines enforces a fixed limit of 40 dBA during all hours of the day. This limit is more restrictive than in Ontario, where allowances for higher sound levels are made when the wind speed increases. This limit is to be measured at the exterior of the nearest permanently occupied residence and/or the property line of undeveloped land zoned for future residential use. The siting must conform to ISO 9613-2, which is referenced by other jurisdictions, including Ontario, for use in impact assessment. The modeling is also similar to other jurisdictions, requiring the sound power level (PWL) to be estimated for 8-10 m/s wind speeds at a 10 m height. Should the modeling demonstrate that the estimated level is close to the acceptable limit, the policy requires that a risk assessment be conducted prior to approval. Testing of the sound levels of the facility post-construction is performed if a complaint is filed.

3.2.4 Québec - Instruction Memo 98-01 on Noise (Note: revised as of June 9, 2006) (Reference R5)

Quebec does not have a specific document relating only to wind turbines; the applicable paper discusses noise from all fixed sources. Different limits have been assigned based on the land use of the receiving property and the residual level of noise in the area. The location of measurement is at a distance 3 m or more from reflective structures, and 0.5 m from an open window. All sound levels averaged during a period of one hour must comply with these limits. There are two main categories of land use: sensitive zones (i.e. residential, hospitals, schools) and non-sensitive (agriculture and industrial use) zones. See table below for limits. In the case of a dwelling on agricultural land, the limits for a sensitive zone apply. For dwellings on industrial land, a 50 dBA nighttime limit and a 55 dBA daytime limit will apply. In terms of sensitive areas, the noise limits are comparable to those in Ontario, although there are different levels for day and night. However, an exception is given in the case of industrial and agricultural land, unless a dwelling exists, for the sound level limits to be much higher. The sound that is measured at the receiving property is based on an equation given in the document, accounting for the equivalent sound level of the source, and corrective factors to account for impact noise, tonal noise and

special situations. However, the length of time that applies is up to the discretion of the person performing the evaluation, and should correspond to the current practice methods. Similarly, when measuring background noise, measurements taken that cover the full reference range are favoured, but not required. Post construction, measurements must be taken to ensure the compliance of the facility with the appropriate limits.

Table 3.3 Noise Regulations in Quebec

Zone	Night	Day
I – Sensitive – Single family dwellings, schools, hospitals	40dBA	45dBA
II – Sensitive – Multi-residential and camping areas	45dBA	50dBA
III – Sensitive – Commercial use and park land	50dBA	55dBA
IV – Non-sensitive – Industrial or Agricultural	70dBA	70dBA

3.2.5 Oregon - Revising Oregon's Noise Regulations for Wind Turbines (Reference R6)

Oregon has recently undergone a revision to its existing noise standards, which were last updated in the 1970s. There are two tests, or limits, that apply in the case of wind turbine developments, the Table 8 test (refers to Table 8 in the regulation) and the ambient degradation test. The authors of the revision have taken steps to coordinate their standard with that of the British and Australian guidelines on wind turbine noise. They have assumed a standard ambient background L_{50} of 26 dBA, although extensive documentation can be submitted for background noise greater than this level. The noise level limit is not allowed to increase the ambient noise levels by 10 dBA in any one hour, thus having an assumed limit of 36 dBA, which is lower than the MOE limits. It is also low enough to respect the WHO guidelines for indoor levels without accounting for sound reduction through walls. This limit applies to both daytime and nighttime, just like the MOE limits. However, unlike the Ontario requirements, there are also setbacks that must be adhered to; a minimum of 350 m for a consenting owner, and 1000 m between the nearest wind turbine and the property of a non-consenting owner. The methods of evaluating the sound created by the wind turbine development use the same methods that the majority of manufacturers provide to make things easier. The project must be evaluated under the maximum

sound power level conditions according to IEC 61400-11 (8 m/s at 10 m height), but no correlation between 10 m and hub height is assumed.

Table 3.4 Oregon's Table 8 Limits, dBA

Statistical Descriptor	Daytime (7 a.m. – 10 p.m.)	Nighttime (10 p.m. – 7 a.m.)
L_{50}	55	50
L_{10}	60	55
L_1	75	60

NOTE: Maximum Permissible levels for New Industrial and Commercial Noise Sources, dBA - As in Bastasch, Noise-Con 2004, originally from OAR 340-35-035.

3.2.6 Pennsylvania - Wind Farm Model Ordinance Draft 12-08-06
(Reference R7)

The draft document developed in Pennsylvania is a model document prepared for the use by different local municipalities. It is not the regulation for the entire state. Local municipalities can use the draft document to prepare their own policies and guidelines. There is only one limit in the Pennsylvania draft, which applies to both daytime and nighttime. The sound level limit is slightly unclear however, because it states that the audible sound "shall not exceed fifty (55) dBA" (note that this has been correctly recorded here, the discrepancy between the written word and the numerical value given in parentheses). This value is much higher than the value given in the MOE regulation, and also equals the WHO recommendation for serious annoyance in an outdoor setting. [See Reference R1]. There is no mention or consideration of ambient sound levels, but waivers to this sound level may be considered. It also does not mention whether this is an hourly limit or not. The point of receiving is considered to be the "exterior of any occupied building on a non-participating Landowner's property." There are also associated setbacks that must be followed. The distance between a wind turbine and the nearest building on the same property must be a minimum of 1.1 times the turbine height. The distance between a turbine and the nearest occupied building on a non-participating property must be at least 5 times the hub height of the turbine. These setbacks exist in response to both safety and noise related issues.

Table 3.5. Pennsylvania Draft Ordinance

	Receiving Property Designation					
Source	**Residential (Class A)**		**Commercial (Class B)**		**Industrial (Class C)**	
	Daytime	Nighttime	Daytime	Nighttime	Daytime	Nighttime
Class C	60 dBA	50 dBA	65 dBA	55 dBA	70 dBA	60 dBA

Note: Daytime is considered to be 7am – 10pm
Nighttime is considered to be 10pm – 7am

3.2.7 Washington - Chapter 173-60 WAC Maximum Environmental Noise Levels (Reference R8)

In Washington State, there is no specific regulation for wind turbine noise, so sound levels must comply with the limits in the environmental noise legislation. This results in noise limits that are the highest among those reviewed here (along with Maine), much higher than the MOE limits. Noise level limits are dependant upon the designation, or class, of both the source property and the receiving property. Wind turbines, as a source, would fall under neither Class A, residential, nor Class B, commercial; therefore they would be considered Class C. The hourly sound levels must not exceed the listed measures anywhere within the property line of the neighbouring property. However, it is also mentioned that local governments should adopt their own noise policies. Chapter 173-58 WAC details the proper sound level measurement procedures to follow.

3.2.8 Michigan - Michigan Wind Energy System Siting Guidelines Draft #8 (Reference R9)

The Michigan wind energy draft is meant to apply to smaller local governments and non-urban areas that do not have other existing guidelines in place. There are different guidelines for small, on-site use wind turbines, and larger developments meant for grid energy use.

The Michigan guideline considers the measure of the ambient sound level to be L_{90} and it is assumed to be less than 55 dBA in most cases. The guidelines state that the sound level generated by the turbines should not exceed 55dBA at any property line, unless with written

consent. This level is similar to the one developed by the State of Pennsylvania (see above). During any one hour, this is not to be exceeded for more than three (3) minutes. Should the ambient sound level be greater than 55dBA, then the sound level limit is L_{90} + 5dBA, L_{90} as the measured ambient sound level. For demonstration of the compliance to these limits, a submission following IEC 61400 and ISO 9613 methods must be completed for project approval, and within 60 days of the project's completion, the levels must be verified to ANSI S12.18 by a professional third party. The State of Michigan is the only other jurisdiction among those reviewed that requires submission of noise impact according to ISO 9613 like the Ontario MOE requirements. However, the noise level limits are much higher than the MOE limits.

3.2.9 Maine - Chapter 375 No Adverse Environmental Effect Standard of the Site Location Law

(Reference R10)

This is another example of a state that has written a standard for use where local governments have not written their own. Local standards take precedence over the state limits unless they contain values over 5 dBA higher for the same situation. As with the Washington sound level limits, the noise limits within this document apply to all environmental noise, including wind turbines, resulting in much higher values. The noise limits apply to new and expanding developments and are measured at the property line, but no specific information is provided on how the sound levels from wind farms are to be modeled. The limits vary based on the zoning of the receiving property or the ambient sound level, and are different for day and night. The noise limits are summarized in the Table 3.6.

Table 3.6 Regulations in Maine

Receiving Property	Daytime Sound Level Limit (7am – 7pm)	Nighttime Sound Level Limit (7pm – 7am)
Any location that is not zoned for commercial, transportation or industrial	60 dBA	50 dBA
Any location that is zoned for commercial, transportation or industrial	70 dBA	60 dBA

These limits apply unless the ambient sound level prior to development is equal to or less than 45 dBA during the daytime hours and 35 dBA during the nighttime hours, such as in a rural environment. Should this be the case, the limits are required to be 55 dBA during the day and 45 dBA during the night; a 10dBA increase, regardless of the zoning of the receiving property. There are two methods allowed to demonstrate the level of the ambient sound, by performing measurements, or, if the population within a 3000 m radius of the property is greater than 300 people, the state allows the assumption that the ambient level exceeds 45 dBA during the day and 35 dBA at night. Additionally, if it can be proven that the development will not emit sound levels greater than 50 dBA during the day and 40 dBA during the night, there is no requirement to estimate or measure the sound levels.

There are further requirements for short duration repetitive sounds and tonal sounds. There are also regulations on the personnel carrying out the measurements, the instrumentation and calibration necessary, and the location, configuration and environment conditions for the microphones, but not necessarily in the specific case of applying the measurements to wind farms.

3.2.10 New York - Power Naturally: Examples of NY Local Government Laws/ Zoning Provisions on Wind

(Reference R11)

The state of New York does not have a standard for wind turbine noise, but relies on local governments to develop their own, which many have. The town of Clinton, NY, is one such municipality, and is a good indication of what the standards in New York State are like. The limit, which applies at any time of the day, is $L_{10} \leq 50$dBA, meaning that in any one hour, 50 dBA can be equaled or exceed only ten percent of the time. The sound level is measured at the nearest residence, located off-site, which may or may not include more than one property. If the owner consents to a higher threshold of noise, a waiver can be granted allowing an increase to the noise level limit. If the ambient sound, which is defined as the highest whole number in dBA exceeded for more than 5 minutes per hour, is greater than 50 dBA, then the sound level limit is the ambient sound level plus 5dBA. These levels are higher than the MOE limits, but remain

just below the level of moderate annoyance for outdoor noise of 50dBA listed in the WHO Community Noise document.

3.3 NOISE LIMITS FROM EUROPE

Europe has long been at the forefront of developing and utilizing wind energy as an energy source. It is not surprising that they have been able to develop noise limit standards to a higher degree than North America. It does not mean that they are more complicated; in fact, they are often simpler than North American noise limits. The following are some examples of noise level limits of wind farms from European countries.

3.3.1 UK - ETSU-R-97: The Assessment and Rating of Noise from Wind Farms (Reference R12)

The document produced by the Working Group on Noise from Wind Farms is perhaps the most comprehensive document of all the ones reviewed here. It covers the history and philosophy of developing noise limits, as well as a thorough explanation of the current limits. The document regulates a separate limit for daytime and nighttime noise levels. These are in part based on the background noise level, $L_{A90,\ 10min}$, which is determined by continuous monitoring of ten minute intervals over a period of time, correlated with different average wind speeds measured over the same period. There is no distinction between zoning or the use of the receiving property as in the Ontario MOE limits.

The principle of the limits is that the wind farm noise is limited to 5 dBA above the wind dependent background noise level, subject to a minimum value at low wind speeds. During the daytime, this minimum value in low noise environments is not to be lower than a range between 35 dBA and 40 dBA, depending on the number of dwellings and the effect on the amount of energy produced. At night, this minimum value is 43dBA. Both of these limits are recommended to be increased to 45 dBA in cases where there is financial benefit to those involved. As with other standards, a 5 dB penalty is incurred if tonal characteristics occur. Should this appear to be the case, a tonal assessment must be performed, consisting of 2 minute

measurements. The document does not require an impact assessment of the development to be submitted.

3.3.2 Ireland - Wind Energy Development Guidelines
(Reference R13)

Ireland has adopted noise limits that are similar to the UK limits for wind turbines. The daytime limit is allowed to be the maximum of 45 dBA or 5 dBA above the background level, L_{90}. However, if the current level of background noise is very low, below 30dBA, the noise level limit will fall in the range of 35 dBA to 40 dBA. The standard does not state how this limit will be determined. The nighttime limit is fixed at 43dBA. These noise levels are comparable to the Ontario MOE limits. The Irish Guidelines have no set-back limits. Instead it states and we quote, "In general noise is unlikely to be a significant problem where the distance from the nearest turbine to any noise sensitive property is more than 500 m." [Reference R13). The document has stated that in order to determine the ambient sound level, measurements should be taken at ten minute intervals, however, it has not dictated how the wind farm noise level should be predicted or what steps to determine the impact of the wind farm should be taken.

3.3.3 Denmark - Document: Statutory Order From the Ministry of the Environment No. 304 of May 14, 1991, On Noise From Windmills
(Reference R14)

Denmark's noise limits are fixed, ambient conditions having no effect, and apply to both daytime and nighttime with no distinction. This is in contrast to the MOE limits, which may depend on both the wind speed and the hourly background level; however, the actual sound level limits have a direct comparison to Ontario's. When the wind farm is located in the open country, the outdoor sound level limit is 45 dBA at the nearest neighbouring property, considered to be any residential building other than the "private house of the windmill owner". For wind farms closer to residential areas, the fixed limit is 40 dBA.

3.3.4 Germany - Document: Lärm (Techniche Anleitung Lärm, Germany), 1998
(Reference R15)

The German noise limits are defined in the above document and are outlined in Table 3.7 below.

Table 3.7. German Noise Regulations.

Area	Day Time	Night Time
Industrial Area	70 dBA / 65 dBA	70 dBA / 50 dBA
Mixed residential area and industry or Residential areas mixed with industry	60 dBA	45 dBA
Purely residential areas with no commercial developments	55 dBA / 50 dBA	40 dBA / 35 dBA
Areas with hospitals, health resorts etc.	45 dBA	35 dBA

Calculation of sound propagation is done according to ISO 9613-2. All calculations have to be done with a reference speed of 10 m/s at 10 m heights.

3.3.5 Netherlands: Bseluit van 18 oktober 2001, houdende regels voor voorziengen en installaties; Besluit voorziengen en installaties milieubeheer; Staatsblad van het Koninkrijk der Nederlanden 487

(Reference R16)

Noise regulations specific to wind turbines in the Netherlands were issued in 2001, but are currently under review by the Dutch authorities. The 2001 wind farm noise limits followed a wind speed dependent curve and are shown in Table 3.3.2 for night time noise limits. The limit for day time started at 50 dBA and for evening hours, the limit started at 45 dBA and increased to 50 dBA for a speed of 12 m/s.

Table 3.8. 2001 Netherlands Noise Assessment Limits – Night time.

Wind Speed at 10 m height (m/s)	1	2	3	4	5	6	7	8	9	10	11	12
Wind Turbine Noise Criterion, dBA	40	40	41	41	42	42	43	44	46	47	48	50

As noted above, the 2001 assessment process is currently under review. In the interim, the Dutch authorities use their established general limits, not specific to wind turbines, of 40 dBA (night), 45 dBA (evening) and 50 dBA (day).

3.4 WIND FARM NOISE LIMITS FROM AUSTRALIA AND NEW ZEALAND

The wind farm noise limits of these two countries relate more to those of the European countries rather than North America. They require extensive data collection for the determination of ambient sound levels, and the sound level limits themselves are among the lowest, being developed in accordance with the World Health Organization document Guidelines for Community Noise. The standards as written are much more detailed in their requirements, and thus are of great value when reviewing noise standards for wind farms.

3.4.1 Australia - Planning Bulletin 67: Guidelines for Wind Farm Development and Environmental Noise Guidelines: Wind Farms

(References R17 and R18)

There are documents from both Western and Southern Australia; however, there is only one set of noise limits since the Western Australia guidelines reference the South Australian noise limits. The South Australian guidelines have elected to define fixed limits that must be followed, and are among the strictest that are reviewed here. The limit during the daytime is 35 dBA or the background noise plus 5 dBA, $L_{A90,\ 10}$ + 5 dBA. The other jurisdiction that has a comparable noise level limit is the American state of Oregon. Both Australia and Oregon have limits that are more strict than Ontario. In order to determine the ambient levels, extensive data collection of noise levels over continuous 10-minute intervals must be examined according to a regression analysis. Wind speeds must be measured at 10m above the ground and also analyzed over the same periods. In order to determine the sound level limit compliance, the sound is measured not at the property line, but at a distance of up to 20 m away from the nearest house. In addition, demonstration is required that shows the operational sound levels do not exceed the

predetermined limits or else restrictive measures may be taken to limit the operation of the wind farm.

3.4.2 New Zealand - NZS 6808: 1998: Acoustics – The Assessment and Measurement of Sound From Wind Turbine Generators
(Reference R19)

New Zealand also has a fixed sound level limit, as with other countries. At any residential home, the sound level limit outside of the house must not exceed 40 dBA. This limit has been selected to achieve an indoor sound level that corresponds to the values recommended in the WHO Guidelines for Community noise. If the background noise, L_{95}, exceeds 35 dBA, then the sound level limit is permitted to be L_{95} + 5 dBA. These levels are higher than the strict limits of Australia and Oregon, and are comparable to the Ontario and Danish sound level limits. This limit is to apply at the property line of the nearest residential property, or the "notional boundary" if the dwelling is located on a large rural property. The standard allows the sound levels from the wind farm development to be estimated using the sound power levels supplied by the manufacturer, but for determination of the ambient sound levels, extensive data collection over a period of ten to fourteen days is required. Post-installation verification is not always required by the standard.

3.5 DISCUSSION

The assessment of wind farm noise and their impact on sensitive receptor locations as applied in different jurisdictions were described above. The main differences between the different regulations and guidelines are twofold:

a) The acceptable noise limits; and
b) The evaluation of receptor noise levels from the cumulative operation of the turbines in the wind farm.

The commonality among the regulations and guidelines is quite striking. All of them accept the IEC Standard 61400-11 (Reference 26) procedures to establish the sound power levels of wind turbines as well as the determination of the hub-height and/or the 10 m high wind speeds within

the operating range of the wind turbines. In addition, none of them consider the effect of atmospheric classes on night time operational character of the wind farm such as higher-than-expected wind speeds at hub-height compared to the conventional wind-shear prediction methodologies.

It is seen therefore, that the main difference between the regulations and guidelines is the noise limits and hence a comparison table is given below in Table 3.8 below. Table 3.8 summarizes only the night time noise limits. Note that direct comparisons of limits may not be appropriate as different jurisdictions have different legal, procedural and assessment frameworks.

Table 3.8. Approximate Ranking of Noise Regulations (Night time limit, dBA).

Jurisdiction	Noise Limit, dBA
Australia	35 and adjusted higher with wind speeds
Germany and Oregon, USA	35 to 36
Alberta, British Columbia, Quebec, Denmark, and Netherlands (Interim)	40
United Kingdom, Ireland, Ontario and New Zealand	40 and adjusted higher with wind speeds
New York, Maine, Pennsylvania and Washington, USA	50 and higher

3.6 SUMMARY

Regulations and guidelines from different jurisdictions in North America, Europe and Australasia were highlighted in this section. These are some of the examples of different assessments of noise impact from wind turbines and wind farms. It was shown that some jurisdictions have special legislation concerning wind turbines, while others apply general recommendations. Different descriptors such as L_{Aeq} or $L_{A90,\ 10\ min.}$ were used to quantify wind turbine noise levels. The noise levels could be either absolute values or related to the background noise level. The background noise levels could be standardised, measured or related to ambient wind speeds. The review of the regulations and guidelines of the jurisdictions investigated showed that the Ontario, Canada assessment process is similar to other jurisdictions.

4.0 REVIEW OF AVAILABLE LITERATURE

A substantial portion of information, both scientific and non-scientific is available in the open literature. The literature review focussed mainly on the following:

I) Metrological effects on wind turbine noise generation;
II) Assessment procedures of wind turbine noise levels and their impact;
III) Particular characteristics of wind farm noise; and
IV) Human responses to wind farm noise levels.

NOTE: The literature review did not consider material that was available after June 2007.

The exact noise generation mechanisms of wind turbines and control techniques of wind farm and turbine noise were not reviewed by the current investigations. Relevant databases such as journals through ScholarsPortal, internet and conference proceedings were searched for the literature. Proceedings from a few conferences were searched also. It must be pointed out that conference papers are usually accepted without proper peer-reviews. Only a few articles were available and are listed in the main reference list. The results of the review are summarized below.

4.1 METEOROLOGICAL EFFECTS

The paper by P. Botha of New Zealand has shown the effects of weather conditions on wind speed profiles with height (Reference 22). This is the only paper, to our knowledge, that has scientifically shown variation of wind speeds with heights from measurements conducted at four sites – two (2) in New Zealand and two (2) in Australia. The measurements were conducted for a period of one year. The two Australian sites (Sites 1 and 2) were flat terrain and the two New Zealand sites (Sites 3 and 4) were complex terrain. Wind speeds were collected in 10 minutes intervals and the composite results from Reference 22 are reproduced below as Figure 6.1.

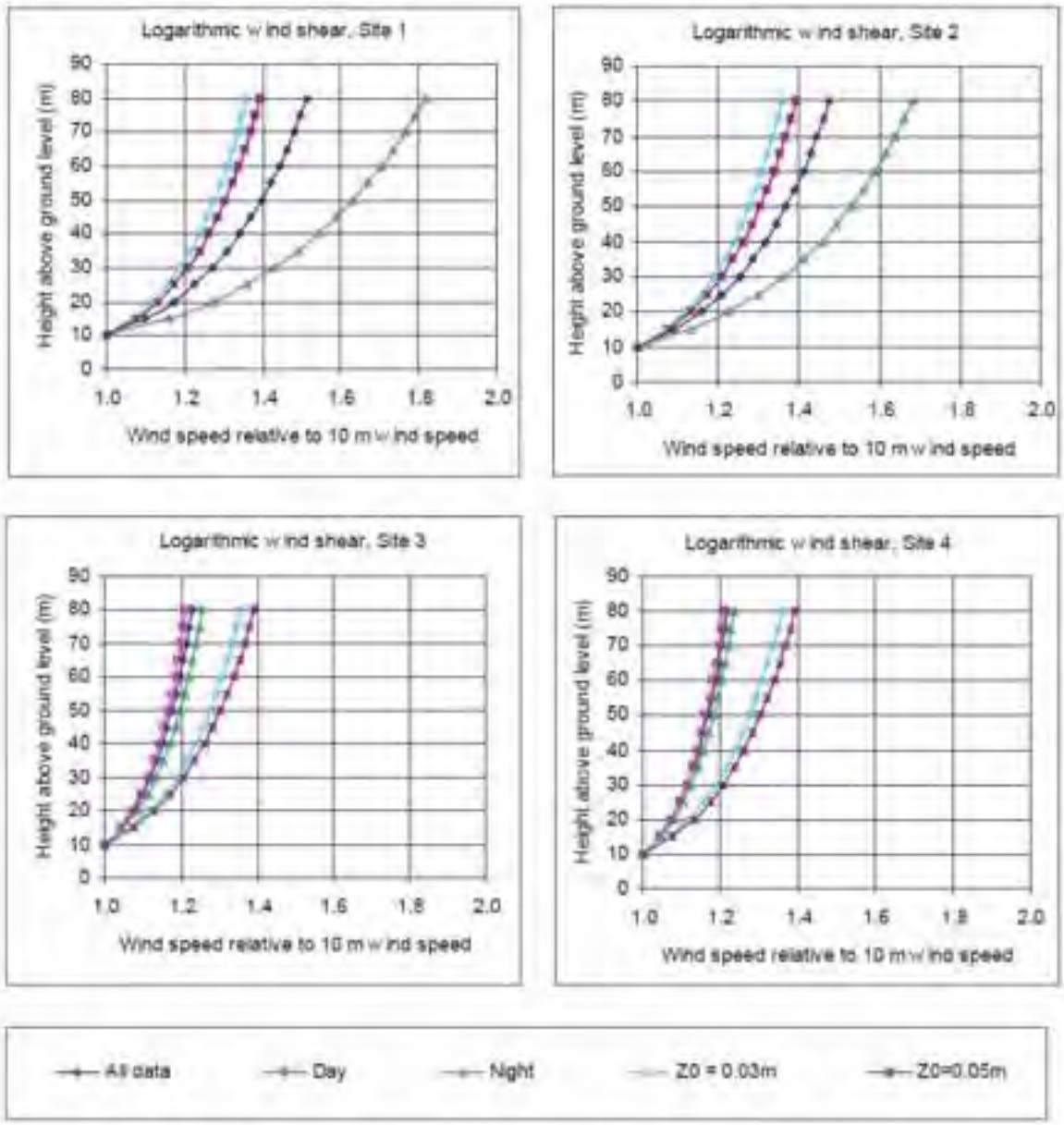


Figure 4.1. Wind speed profiles at 4 different sites

(From Reference 22 – Figure 1)

Five graphs were plotted for each site: Composite profile for all day data, profile for day data, profile for night data, IEC standard logarithmic profile with the shear coefficient from observed site conditions (Z_0 = 0.03) as well as the standard shear coefficient, Z_0, of 0.05. The results do indicate that for some terrains, the hub-height wind speeds can be more at night time than during

day time when compared to the 10 m height wind speeds. However, the local conditions determine the meteorology and one cannot, as analysed by van den Berg, apply information from far-off sites to local conditions. Further, for the terrains in Australia, the Sound Power Levels at night time would be around 2 dBA more than predicted from standard procedures from day time profiles. It must also be highlighted that the measurements of Reference 22 clearly showed the wind profiles were nearly identical between day and night time for the complex terrains of New Zealand.

The main conclusions of this section are: a) wind shear is an important parameter that must be accounted for appropriately in any assessment; and b) the effect of meteorology is highly localized and strong conclusions cannot be easily transferred from site to site.

4.2 ASSESSMENT PROCEDURES OF WIND TURBINE NOISE LEVELS

Papers by Botha (Reference 22), Sloth (Reference 23) and Sondergaard (Reference 24) are examples of work undertaken to look into the assessment procedures currently applied in many jurisdictions. These three papers evaluate the application of sound power levels of wind turbines standardized to a 10 m height wind speed. The main conclusion of these papers is that the normal procedure of basing the analysis and assessment on the standardized sound power levels is not sufficient. Sloth shows a method to incorporate the relevant sound immission data with appropriate uncertainties accounted for so as to minimize noise annoyance. One such method is suggested in Appendix F. Sonderggard has also pointed out that additional research is required to account for many of these deficiencies. References 27 and 28 showed that many of the propagation models have uncertainties associated with them and can produce “less than accurate” results if local weather conditions are not properly modelled.

One of the main criticisms about noise assessment process of wind farm application is that the sound power levels of wind turbines are measured and reported following the procedures of the IEC-Standard [Reference 26]. It must be noted that the IEC 61400-11 standard for wind turbine noise is a measurement standard and is primarily intended to define how manufacturers obtain

and report the sound power from wind turbines under standardized wind shear conditions. It does not prevent one from adjusting the sound power to reflect the actual site specific wind shears obtained from testing.

4.3 PARTICULAR CHARACTERISTICS OF WIND FARM NOISE

Two main issues are usually discussed regarding the source characteristics of noise generated by wind turbines – low frequency or infra sound and the swishing (thumping) sound normally termed as the amplitude modulation phenomenon.

The measurement results from wind turbines, such as the data reported by van den Berg (Reference 1) and Howe and McCabe (Reference 28) show the absence of significant low frequency components and the same conclusion is highlighted by Regan and Casey ((Reference 25) in their primer on wind turbine noise aspects. The results of Reference 1 (van den Berg's dissertation) show that the infra-sound levels, even if present, are well below the threshold of perception.

The nature of the amplitude modulation phenomenon and its relationship to the acoustical *beating* phenomenon was already discussed in Section 2.4. The different principles of these phenomena will not be discussed further. Due to the nature of the amplitude modulation phenomenon, the swishing or thumping exists all the time. Only van den Berg has attempted to show that the modulation gets stronger at night time. Our review of van den Berg's work was presented in Section 2. We were unable to find other works in the literature that provide evidence for increased modulation at night time. The only effect, discussed in the next section, of the phenomenon is the modulated sound becomes audible at night time. This could be due to quieter ambient sound at night time. As Reference 18 states, "In summary, the modulation in the noise from wind turbines is not yet fully explained and will not be reduced in the near future and is therefore a factor of importance when discussing noise annoyance from wind turbines."

Reference 30 has addressed the issues connected with modulation. One of its principal findings is and we quote, "the common cause of complaint was not associated with low-frequency noise,

but the occasional audible modulation of aerodynamic noise, especially at night. Data collected showed that the internal noise levels were insufficient to wake up residents at these three sites. However, once awoken, this noise can result in difficulties in returning to sleep." Reference 30 does not use the term "beating" to describe the amplitude modulation that has been observed as well as measured. It has been referred to simply as "aerodynamic modulation." Reference 30 also points out that the many mechanisms hypothesized by van den Berg (Reference 1) for the modulation behaviour are debatable. It was shown in Section 2 during the current investigation that the data provided by Reference 1 do not support its findings. Further, no support was seen for the modulation behaviour to get stronger under stable atmospheric classes at night time as postulated by van den Berg. The same points were presented in Section 2 of this report. Finally, Reference 30 discussed the many possible mechanisms that can cause the amplitude modulation as well as provided measurement results to show that modulation can produce changes in noise levels of the order of 10 dB. It concluded that detailed research is required to settle many of the unknowns that can cause the amplitude modulation.

4.4 Human Responses to Wind Farm Noise Levels

A considerable body of literature is available on this subject, both scientific and anecdotal. Only a few of the scientific and review articles, References 5, 12, 18, 20, and 25, are highlighted in the current study.

According to Reference 25, the only health effect of wind turbine noise is annoyance. Sheppard et al. (Reference 12) conducted a laboratory study with unbiased subjects and played different sounds including wind turbine noise at various levels. Since the study was conducted in early 80s, the old type wind turbines were included in their investigations. Their study developed a human response criterion for wind turbine generators based on receptor received noise levels and termed it 'Perception Detection Threshold.' The study showed that the thresholds for wind turbine noise were below the thresholds of general tones. After validating the usefulness of the response function, the following annoyance table, based on an old ISO standard, now defunct,

was recommended to evaluate the community response. The annoyance table is presented in Table 4.1 below.

Table 4.1 Estimated Community Response to Wind Turbine Generator Noise

(From Reference 12 –Figure 12 of Reference 12, based on an ISO standard)

Amount in dB by which the rated noise exceeds Threshold Level	Estimated Community Response	
	Category	**Description**
0	None	No Observed Reaction
5	Little	Sporadic Complaints
10	Medium	Widespread Complaints
15	Strong	Threats of Community Action
20	Very Strong	Vigorous Community Action

NOTE: **Rated Noise Level –** The actual noise level that would be measured at the receptor locations;
Threshold Level – The average ambient sound level that would exist in areas around the wind farm site.

A study, similar to that of Sheppard (Reference 12) is required to evaluate the detection threshold for modern wind turbines.

The annoyance study of Pedersen and Waye concluded that annoyance increases with sound levels. However, these annoyance studies have very small sample sizes and focussed on subjects living close to wind farms. No blind survey was conducted. Only 65 of the 356 respondents were exposed to noise levels of 37.5 dBA and above. The following categories – perception, dose-annoyance, sensitivity, attitude to source, visual exposure and rural setting – were included in the survey. The correlation between most of the categories and noise levels were small. The noise level and annoyance response was proportional to the exposure level. However, the sample size was too small. The subjects had prior exposure to wind turbines, making the sample biased. It must be acknowledged that the research of Pedersen and Waye has provided important insights into the human response of wind turbine noise and has considered important parameters.

However, the work of Pedersen and Waye need to be expanded to include large enough samples with unbiased subjects.

Finally, one of the arguments presented by anti-wind farm proponents is that 'beating' increases human annoyance. The only result that can be culled from the literature, Reference 18, is that the modulation frequencies, 0.5 to 1 Hz for wind turbines, are such that the wind turbine noise can be detected. Since major studies on wind turbine beating and human annoyance have not been conducted, major conclusions are not possible at this stage.

4.5 SUMMARY

Available literature on wind turbine noise was reviewed and the review focussed on four categories, considered important to the Ministry's stated goals. The results of the review were presented in this section. The main findings of this section are:

A) The local terrain conditions can influence meteorological conditions and can affect the expected noise output of the wind turbines;
B) Assessment procedures applied in different jurisdictions are quite similar in their scope;
C) Wind farm noise do not have significant low-frequency (infrasound) components;
D) Further study needed in order to determine effect of modulation on human annoyance.

5.0 REVIEW OF MOE'S NOISE POLICIES AS APPLIED TO WIND FARM NOISE

The Ministry of the Environment released a guideline document, "Interpretation for Applying MOE NPC Technical Publications to Wind Turbine Generators" in 2004. The above guidance document was to assist proponents of wind turbine installations in determining the list of necessary information to be submitted when applying for a Certificate of Approval (Air and Noise) under Section 9 of the *Environmental Protection Act*. A summary of these interpretations by John Kowalewski was also published in the Canadian Acoustics Journal (Reference 33). The noise guidelines in MOE publications NPC-205/NPC-232 as well as the wind generated noise levels were applied to set the noise limits. These three documents are enclosed in Appendices A, B and C.

5.1 MOE'S ASSESSMENT PROCESS

The assessment procedures of MOE are summarized below for completeness sake:

I) All wind farm applications must obtain a Certificate of Approval from MOE. If individual wind turbines have a capacity of 2 MW or more, the project must undergo an Environmental assessment review;

II) If there are no receptors within 1000 m of the wind farm boundary, no detailed noise assessment is necessary;

III) The noise limits are established based on the location of the receptors in Class 1 & 2 areas and Class 3 areas.

IV) The sound power levels of the wind turbines are to be obtained from the standard procedures contained in IEC Standard 61400-11, by applying the wind speeds at 10 m height above ground. [Reference 26].

V) The sound pressure levels at each receptor location are to be evaluated applying the procedures of ISO 9613.

VI) The noise impact is assessed by comparing the predicted noise levels at individual receptor location with the noise limits established in Step III. The noise impact is evaluated at each wind speed over the operating range of the wind turbine specifications.

The noise limits are wind speed dependent and are summarized in Table 5.1 below.

Table 5.1 Ontario Noise Assessment Limits

Wind Speed (m/s) @ 10 m height	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Wind Turbine Noise Criterion NPC-232 (dBA) (Rural) – Class 3 Areas	40	40	40	43	45	49	51	53
Wind Turbine Noise Criterion NPC-205 (dBA) (Urban) – Class 1 & 2 Areas	45	45	45	45	45	49	51	53

The MOE procedures outlined in Appendix A do not explicitly discuss the application of penalties for source character or apply particular meteorological conditions.

The MOE's assessment process is very similar to the procedures applied in the New Zealand (Reference R19), as it recognizes the usefulness of masking effects of ambient wind. The implicit assumption is that it is the ambient wind that generates the noise of wind turbines as well as background noise levels at receptor locations.

The Ministry's noise assessment guidelines for stationary sources of sound are based on the premise that noise from the stationary sources may be annoying when it is audible over and above the level of the so-called "ambient" or surrounding environmental "noise climate" at a particular location. However, audibility does not necessarily mean annoyance. Furthermore, annoyance is not the same for the entire population; people at the extreme of the statistical distribution may be annoyed at different noise levels. Such an approach was considered a 'sound' policy from the inception of the Model Municipal Noise Control by-Law issued by MOE in August 1978. The policies provide adequate protection from adverse noise pollution impacts as well as not imposing restrictive conditions on industrial noise sources. However, the MOE's

assessment, even though has provided a very simple procedure, has been very general in its overall scope. Two issues need to be resolved and are highlighted below.

5.2 PENALTY FOR SOURCE CHARACTER

The guideline document that deals with noise assessment of wind turbines, enclosed in Appendix A, does not explicitly discuss penalties for characters such as tonal components of the wind turbine noise levels, even though reference to NPC-104 is included in the interpretation document. Further, the Ministry document, NPC-205 (enclosed in Appendix C) contains guidelines for penalties, which must be used if a particular wind turbine was found to contain tonal components. The implicit assumption is that the modern up-wind wind turbines have no dominant tones in their spectrum. It must be pointed out that most of the measurement results do show that the turbine noise spectrum is devoid of dominant tones. However, MOE needs to clarify and include source character adjustments in the main body of the interpretation document and even make references to the procedures contained in the IEC Standard (Reference 26) that are used to determine the presence of tones in the noise spectrum.

5.3 METEOROLOGICAL CONDITIONS

One of the main arguments posed by van den Berg (Section 2) is that meteorological condition affect wind speed profiles with height and that the hub-height wind speed may be higher than predicted with the 10 m high wind speed being low. It was made clear in the review presented in Section 2 that the evidence presented to support these arguments were tenuous at best. However, the works of Botha (Reference 22) and Sondergaard (Reference 24) showed that local terrain conditions can dictate the wind profiles and the measurements of Reference 22 has shown that in flat terrains, the wind speed profile with height cannot be predicted accurately by standard methods such as the logarithmic shear function applied in Reference 26.

It is therefore, possible that, for a ‘worst-case scenario’, the hub-height velocities can be higher than expected thereby resulting in higher-than-expected noise levels with lower masking effect of the ambient wind at receptor locations. Some preliminary evaluations presented in Reference

32 showed that discrepancies of the order of 3 dBA are possible. Such a scenario needs to be accounted for in the Ministry's future updates of the assessment procedures. One example of a possible assessment procedure is described in Appendix F.

5.4 SUMMARY

The assessment procedures, currently, applied in the Province of Ontario by the Ministry of the Environment to evaluate wind farm noise levels were reviewed. The results showed that the procedures may have to be revised to incorporate additional factors. One possible assessment process is suggested Appendix F.

6.0 CONCLUSIONS

As part of the review process of their assessment procedures, the Ministry of the Environment for the Province of Ontario has instituted a work project with different tasks. Four individual tasks were part of the review process.

The results of each of the tasks were presented in the previous sections. The conclusions for each of the tasks were included at the end of the relevant sections. The basic conclusions are summarized below:

A) The research work undertaken by G. P. van den Berg didn't provide scientific evidence to support the few major hypotheses postulated concerning the wind turbine noise characteristics. However, the work of other researchers showed that local terrain conditions can impact the local meteorology and thereby the resulting noise levels;

B) Assessment procedures applied in different jurisdictions showed the current Ministry of the Environment process is similar to other jurisdiction. Further, the MOE process has provided a balanced approach between noise impact and the need for wind farms, based on currently available scientific data.

C) Literature review showed that additional research is still required to make definitive conclusions about wind turbine noise impacts as well as human response to wind farms. In addition, detailed research on meteorological conditions, and their impact on sound generation needs to be undertaken to realise definitive conclusions;

D) The Ministry of the Environment's procedures to assess wind farm noise levels follow a simple procedure that is sound for most situations. However, additional concerns still need to be addressed in the next round of revisions to their assessment process. These revisions may need to be addressed after the results from future research provide scientifically consistent data for effects such as meteorology, human response and turbine noise source character.

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APPENDIX A

INTERPRETATION FOR APPLYING MOE NPC TECHNICAL PUBLICATIONS TO WIND TURBINE GENERATORS

INTERPRETATION FOR APPLYING MOE NPC TECHNICAL PUBLICATIONS TO WIND TURBINE GENERATORS

Noise impacts of proposed wind turbine generators, i.e. wind turbines, are considered in the course of assessing an application for a Certificate of Approval (Air), in accordance with Section 9 of the Environmental Protection Act. The purpose of this guidance document is to assist proponents of wind turbine installations in determining what information should be submitted when applying for a Certificate of Approval (Air). It has been developed in order to provide consistency in the submissions and to streamline the review and approval process.

As a minimum, the information package must include details of the wind turbine design and operation, location of the wind turbine within the specific site and surrounding area as well as summary of compliance applicable to noise. The following defines a template for reports to be submitted to the MOE. This information is supplementary to the information in MOE Publication NPC-233, Information to be Submitted for Approval of Stationary Sources of Sound.

REFERENCES

[1] NPC-102 - Instrumentation
[2] NPC-103 - Procedures
[3] NPC-104 - Sound Level Adjustments
[4] NPC-205 - Sound Level Limits for Stationary Sources in Class 1 & 2 Areas (Urban)
[5] NPC-206 - Sound Levels due to Road Traffic
[6] NPC-232 - Sound Level Limits for Stationary Sources in Class 3 Areas (Rural)
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TECHNICAL DEFINITIONS

"Class 1 Area"

means an area with an acoustical environment typical of a major population centre, where the background noise is dominated by the urban hum.

"Class 2 Area"

means an area with an acoustical environment that has qualities representative of both Class 1 and Class 3 Areas, and in which a low ambient sound level, normally occurring only between 23:00 and 07:00 hours in Class 1 Areas, will typically be realized as early as 19:00 hours.

Other characteristics which may indicate the presence of a Class 2 Area include:

i. absence of urban hum between 19:00 and 23:00 hours;
ii. evening background sound level defined by natural environment and infrequent human activity; and
iii. no clearly audible sound from stationary sources other than from those under consideration.

"Class 3 Area"

means a rural area with an acoustical environment that is dominated by natural sounds having little or no road traffic, such as the following:

i. a small community with less than 1000 population;
ii. agricultural area;
iii. a rural recreational area such as a cottage or a resort area; or a wilderness area.

Point of Reception

"Point of Reception" means any point on the premises of a person within 30 m of a dwelling or a camping area, where sound or vibration originating from other than those premises is received.

For the purpose of approval of new sources, including verifying compliance with Section 9 of the Act, the Point of Reception may be located on any of the following existing or zoned for future use premises: permanent or seasonal residences, hotels/motels, nursing/retirement homes, rental residences, hospitals, camp grounds, and noise sensitive buildings such as schools and places of worship.

For equipment/facilities proposed on premises such as nursing/retirement homes, rental residences, hospitals, and schools, the Point of Reception may be located on the same premises.

NOISE LIMITS

The noise limits for a wind turbine or an array of such units (referred to as a “wind farm”) are set relative to the existing MOE Noise Guidelines in NPC-205/NPC-232 as well as to the wind generated background noise. The proponents are required to demonstrate compliance with the following sound level limits:

Wind turbine installations in Class 1 & 2 Areas (Urban)
Wind speeds below 8 m/s

The lowest sound level limit at a Point of Reception in Class 1 & 2 Areas (Urban), under conditions of average wind speed up to 8 m/s (29 km/h), expressed in terms of the hourly equivalent sound level (Leq) is 45 dBA or the minimum hourly background sound level established in accordance with requirements in Publications NPC-205/NPC-233, whichever is higher.

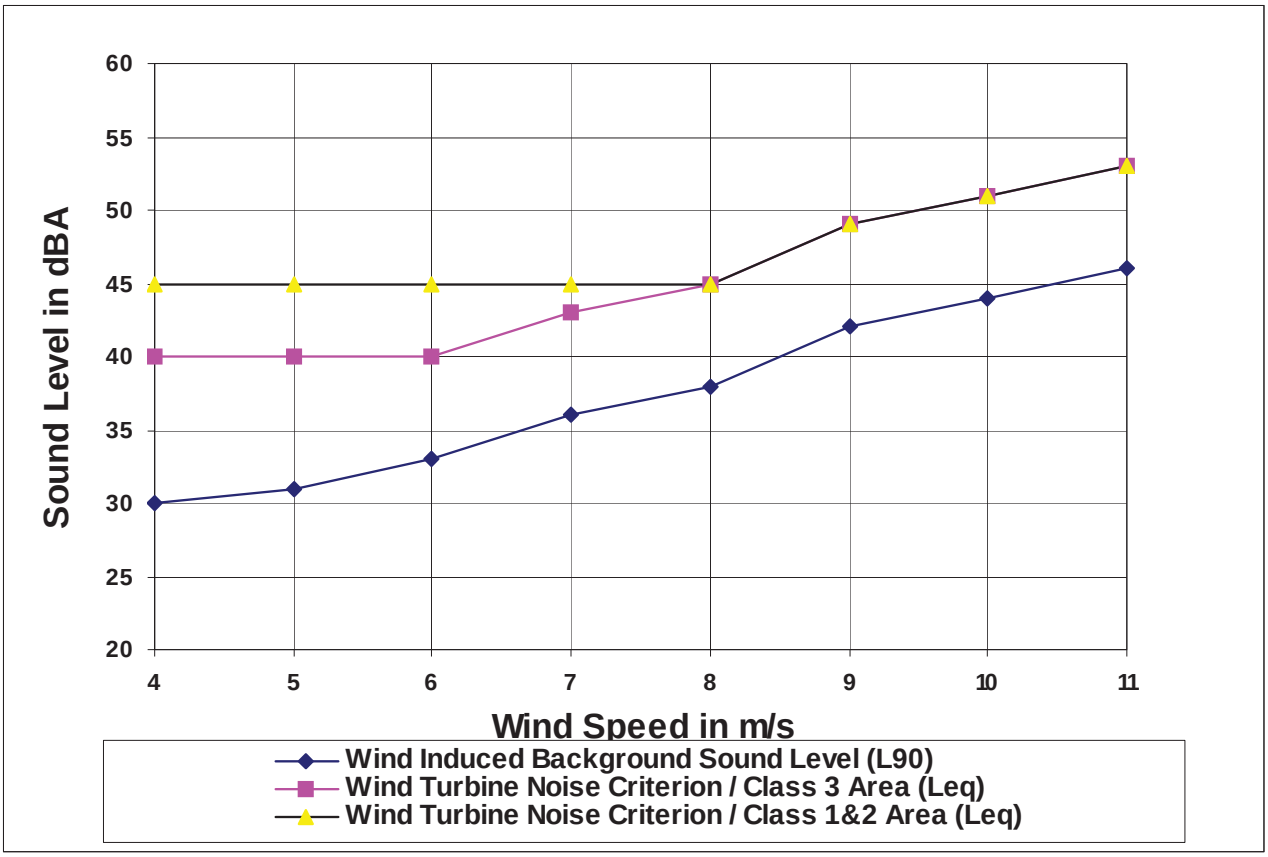
Wind Turbine Installations in Class 3 Areas (Rural)
Wind speeds below 6 m/s

The lowest sound level limit at a Point of Reception in Class 3 Areas (Rural), under conditions of average wind speed up to 6 m/s (22 km/h), expressed in terms of the hourly equivalent energy sound level (Leq) is 40 dBA or the minimum hourly background sound level established in accordance with requirements in Publications NPC-232/NPC-233, whichever is higher.

Wind Turbine Installations in Class 1& 2 and Class 3 Areas
Wind speeds above 8 and 6 m/s respectively

The sound level limit at a Point of Reception in Class Areas 1 & 2 (Urban) or in Class 3 Areas (Rural), under conditions of average wind speed above 8 m/s and 6 m/s respectively, expressed in terms of the hourly equivalent energy sound level (Leq), is the wind induced background sound level, expressed in terms of ninetieth percentile sound level (L_{A90}) plus 7 dB, or the minimum hourly background sound level established in accordance with requirements in Publications NPC-205/NPC-232/NPC-233, whichever is higher.

A summary of the above limits is shown in figure and table below.



Wind Speed (m/s)	4	5	6	7	8	9	10	11
Wind Turbine Noise Criterion NPC-232 (dBA)	40	40	40	43	45	49	51	53
Wind Turbine Noise Criterion NPC-205 (dBA)	45	45	45	45	45	49	51	53

NOTE:

1. The measurement of wind induced background sound level is not required to establish the applicable criterion. The wind induced background sound level reference curve in the figure above was determined by correlating the ninetieth percentile sound level (L_{A90}) with the average wind speed measured at a particularly quiet site.

2. If the existing minimum hourly background sound level, established in accordance with requirements in Publications NPC-205/NPC-232/NPC-233, is selected as the sound level limit, the measurement of wind speed (for the purpose of determination of wind induced background sound level) is not required. The selected limit applies in the entire range of wind speed under consideration from 4 m/s to 11 m/s with exception of the wind turbine noise criterion values higher than the existing minimum hourly background sound level.

3. Wind Turbine Noise Criterion at wind speeds expressed as fractional values of m/s should be interpolated from the above graph.

REPORT CONTENTS AND FORMAT

The noise report must contain the required information, organized in a clear and concise manner. The report should include the following sections in the given sequence:

1. **Introduction**
   Objectives of report
2. **General Description of Wind Turbine Installation Site and Surrounds**
   Description of the site general environment, including: adjacent zoning, sensitive receiver locations (Points of Reception); suitable mapping of the site and surrounding area, providing elevations of source receivers and intervening structures or topography where applicable to the assessment;
3. **Description of Receptors**
   Detailed acoustical description of the area surrounding the facility including: Identification of the closest and/or the critical Points of Reception, identifying noise sensitive residential or institutional uses - (industrial, commercial uses are also desirable information); Determination of the applicable minimum hourly background sound level limit at the critical Points of Reception, in accordance with NPC 205/232 and NPC-233;
4. **Description of Sources**
   Description of the wind turbine (wind farm) including: manufacturer & model number; Design principle & geometric configuration (horizontal, vertical, upwind, downwind, rotor diameter and centre height, blade type, number of blades, tower height); Power train (direct from rotor to generator, indirect through gearbox); Operating details (single, twin or variable speed, power curve, generator rated power output and rotational speed); Park lay-out (for a wind farm);
5. **Wind Turbine Noise Emission Rating**
   Noise emission levels in terms of sound power level of the wind turbine as a function of wind speed (determined in accordance with IEC 61400-11 method), provided by the wind turbine manufacturer;

6. **Impact Assessment**
   Calculation of the sound pressure level at each critical Point of Reception for each wind turbine or an aggregate of units (wind farm) using ISO 9613 method.
   Noise impact assessment under a "worst case scenario" at the critical Points of Reception, up to a distance of 1000 m from the wind turbine (or closest unit in a wind farm); Impact assessment is not required for Points of Reception farther than 1000 m from the wind turbine (or closest unit in a wind farm);
   Comparison with the applicable noise limit;
7. **Wind Turbine Summary Tables**
   Wind Turbine Source Summary Table and Wind Turbine Assessment Summary Table; (samples attached);
8. **Conclusions and Recommendations**
   Summary of impacts and verification of compliance with the noise limits;
9. **Appendices, etc.**
   Details of measurements and calculations, specifications, plans, eng. dwgs, etc.

WIND TURBINE SUMMARY TABLES

The noise report must contain Wind Turbine Summary Tables, summarising the results of the Acoustical Report and demonstrating compliance. The Wind Turbine Summary Tables must address pertinent source(s) and receptors (Points of Reception).
The information in the Wind Turbine Summary Tables must be presented in two tables:

1. Wind Turbine Source Summary Table
2. Wind Turbine Assessment Summary Table

The following examples of summary tables must be incorporated into the report:

Wind Turbine Noise Emission Summary Table
(add rows for additional sources)

	Wind Turbine ID	Max PWL at wind speed <6 m/s	PWL at selected wind speed in m/s				
			7	8	9	10	11
1	WT6000	93	97	99	100	104	106
2							
3							

Note:
1. PWL denotes Sound Power Level in dB re 10^{-12} Watt
2. Noise emissions of a wind farm are represented by a sum of PWL values for individual wind turbine units.

Wind Turbine Noise Impact Assessment Summary Table

Identify all receptors (add rows for additional Points of Reception)

Point of Reception ID	Receptor Description	Distance to closestWind Turbine (m)	Calculated Sound Pressure Level at Receptor (dBA) at selected Wind Speed in m/s						Sound Level Limit (dBA) at selected Wind Speed in m/s						Applicable Background Sound Level		Compliance with Limit (Yes/No)
			6 or <	7	8	9	10	11	6 or <	7	8	9	10	11	NPC 205	NPC 232	
R1	Residence to East	100	43	44	**48**	**50**	**54**	**56**	45	45	45	49	51	53	46		No
R2	Apt. Bldg. to South	150	40	42	45	47	51	**53**	45	45	45	49	51	53	51		No
R3	Nursing Home to West	200	37	39	42	44	48	50	45	45	45	49	51	53	47		Yes
R4	Residence to North	260	35	38	40	42	46	48	40	43	45	49	51	53		44	Yes

Note: Values in the table which are **underlined/bold** denote an excess over the applicable limit.

APPENDIX B

NPC - 232 - SOUND LEVEL LIMITS FOR STATIONARY SOURCES IN CLASS 3 AREAS (RURAL)

SOUND LEVEL LIMITS FOR STATIONARY SOURCES IN CLASS 3 AREAS (RURAL)

PUBLICATION NPC-232

OCTOBER 1995

Ontario

Ministry
of the
Environment

Cette publication technique
n`est disponible qu`en anglais.

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Ontario

MINISTRY OF THE ENVIRONMENT

Sound Level Limits for Stationary Sources in Class 3 Areas (Rural) Publication NPC-232

October 1995

This Publication establishes sound level limits for stationary sources such as industrial and commercial establishments or ancillary transportation facilities, affecting points of reception in Class 3 Areas (Rural). It replaces Publication NPC-132 "Guidelines for Noise Control in Rural Areas" of the "Model Municipal Noise Control By-Law, Final Report, August 1978".

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1. SCOPE

This Publication establishes sound level limits for stationary sources of sound such as industrial and commercial establishments or ancillary transportation facilities, affecting points of reception in Class 3 Areas (Rural). The limits apply to noise complaint investigations carried out in order to determine potential violation of Section 14 of the Environmental Protection Act. The limits also apply to the assessment of planned stationary sources of sound in compliance with Section 9 of the Environmental Protection Act, and under the provisions of the Aggregate Resources Act and the Environmental Assessment Act.

This Publication does not address sound and vibration produced by blasting; blasting in quarries and surface mines is considered in Reference [7].

The Publication includes an Annex, which provides additional details, definitions and rationale for the sound level limits.

2. REFERENCES

Reference is made to the following publications:

[1] NPC-101 - Technical Definitions

[2] NPC-102 - Instrumentation

[3] NPC-103 - Procedures

[4] NPC-104 - Sound Level Adjustments

[5] NPC-205 - Sound Level Limits for Stationary Sources in Class 1 & 2 Areas (Urban)

[6] NPC-206 - Sound Levels due to Road Traffic

[7] NPC-119 - Blasting

[8] NPC-216 - Residential Air Conditioning Devices

[10] NPC-233 - Information to be Submitted for Approval of Stationary Sources of Sound

[12] ORNAMENT, Ontario Road Noise Analysis Method for Environment and Transportation, Technical Document, Ontario Ministry of the Environment, ISBN 0-7729-6376, 1989

References [1] to [4] and [7] can be found in the
Model Municipal Noise Control By-Law, Ontario Ministry of the Environment, Final Report, August 1978.

2. DEFINITIONS

"Ambient sound level"
means Background sound level.

"Background sound level"
is the sound level that is present in the environment, produced by noise sources other than the source under impact assessment. Highly intrusive short duration noise caused by a source such as an aircraft fly-over or a train pass-by is excluded from the determination of the background sound level.

"Class 1 Area"
means an area with an acoustical environment typical of a major population centre, where the background noise is dominated by the urban hum.

"Class 2 Area"

means an area with an acoustical environment that has qualities representative of both Class 1 and Class 3 Areas, and in which a low ambient sound level, normally occurring only between 23:00 and 07:00 hours in Class 1 Areas, will typically be realized as early as 19:00 hours.

Other characteristics which may indicate the presence of a Class 2 Area include:

- absence of urban hum between 19:00 and 23:00 hours;
- evening background sound level defined by natural environment and infrequent human activity; and
- no clearly audible sound from stationary sources other than from those under impact assessment.

"Class 3 Area"

means a rural area with an acoustical environment that is dominated by natural sounds having little or no road traffic, such as the following:

- a small community with less than 1000 population;
- agricultural area;
- a rural recreational area such as a cottage or a resort area; or
- a wilderness area.

Other technical terms are defined in Reference [1] and in the Annex to Publication NPC-232.

3. ESTABLISHMENT OF LIMITS - OBJECTIVE

The sound level limit at a point of reception must be established based on the principle of "predictable worst case" noise impact. In general, the limit is given by the background sound level at the point of reception. The sound level limit must represent the minimum background sound level that occurs or is likely to occur during the operation of the stationary source under impact assessment.

4. BACKGROUND SOUND LEVELS OF THE NATURAL ENVIRONMENT

The One Hour Equivalent Sound Level (L_{eq}) and/or the One Hour Ninetieth Percentile Sound Level (L_{90}) of the natural environment shall be obtained by measurement performed in accordance with Section 7. The results of the measurements must not be affected by the sound of the stationary source under impact assessment.

The time interval between the background sound level measurement and the measurement of the sound level produced by the stationary source under impact assessment should be minimized as much as possible. Preferably, the two measurements should be carried out within one hour of each other.

5. SOUND LEVELS DUE TO STATIONARY SOURCES

(1) Complaint Investigation of Stationary Sources

The One Hour Equivalent Sound Level (L_{eq}) and/or the Logarithmic Mean Impulse Sound Level (L_{LM}) produced by the stationary sources shall be obtained by measurement performed in accordance with Section 7.

(2) Approval of Stationary Sources

The One Hour Equivalent Sound Level (L_{eq}) and/or the Logarithmic Mean Impulse Sound Level (L_{LM}) produced by the stationary sources shall be obtained by measurement or prediction. The estimation of the L_{eq} and/or L_{LM} of the stationary source under impact assessment shall reflect the principle of "predictable worst case" noise impact. The "predictable worst case" noise impact occurs during the hour when the difference between the predicted sound level produced by the stationary source and the background sound level of the natural environment is at a maximum.

6. PROCEDURES

All sound level measurements of the One Hour Equivalent Sound Level (L_{eq}) and the Logarithmic Mean Impulse Sound Level (L_{LM}) shall be made in accordance with Reference [3].

All sound level measurements of the One Hour Ninetieth Percentile Sound Level (L_{90}) shall be made using a Sound Level Meter capable of measuring percentile sound levels. The meter shall meet the applicable requirements for an Integrating Sound Level Meter of Reference [2]. The measurements shall be carried out following procedures for the measurement of varying sound described in Reference [3].

Sound from existing adjacent stationary sources may be included in the determination of the background hourly sound levels L_{eq} and L_{90}, if such stationary sources are not under consideration for noise abatement by the Municipality or the Ministry of Environment and Energy.

7. SOUND LEVEL LIMITS - GENERAL

(1) For impulsive sound, other than Quasi-Steady Impulsive Sound, from a stationary source, the sound level limit at a point of reception within 30 m of a dwelling or a camping area, expressed in terms of the Logarithmic Mean Impulse Sound Level (L_{LM}), is the lower of:

- the background One Hour Equivalent Sound Level (L_{eq}) obtained pursuant to Section 5; and
- the background One Hour Ninetieth Percentile Sound Level (L_{90}) plus 15 dB, i.e. L_{90} + 15 dB, obtained pursuant to Section 5.

(2) For sound from a stationary source, including Quasi-Steady Impulsive Sound but not including other impulsive sound, the sound level limit at a point of reception within 30 m of a dwelling or a camping area, expressed in terms of the One Hour Equivalent Sound Level (L_{eq}), is the lower of:

- the background One Hour Equivalent Sound Level (L_{eq}) obtained pursuant to Section 5; and
- the background One Hour Ninetieth Percentile Sound Level (L_{90}) plus 10 dB, i.e. L_{90} + 10 dB, obtained pursuant to Section 5.

8. SOUND LEVEL LIMITS - SPECIFIC IMPULSIVE SOUNDS

(1) For impulsive sound, other than Quasi-Steady Impulsive Sound, from a stationary source which is an industrial metal working operation (including but not limited to forging, hammering, punching, stamping, cutting, forming and moulding), the sound level limit at a point of reception within 30 m of a dwelling or a camping area, expressed in terms of the Logarithmic Mean Impulse Sound Level (L_{LM}), is 60 dBAI, if the stationary source were operating before January 1, 1980, and otherwise is 50 dBAI.

(2) For impulsive sound, other than Quasi-Steady Impulsive Sound, from a stationary source which is the discharge of firearms on the premises of a licensed gun club, the sound level limit at a point of reception within 30 m of a dwelling or a camping area, expressed in terms of the Logarithmic Mean Impulse Sound Level (L_{LM}), is:

- 70 dBAI if the gun club were operating before January 1, 1980; or
- 50 dBAI if the gun club began to operate after January 1, 1980; or
- the L_{LM} prior to expansion, alteration or conversion.

(3) For impulsive sound, other than Quasi-Steady Impulsive Sound, from a stationary source which is not a blasting operation in a surface mine or quarry, characterized by impulses which are so infrequent that they cannot normally be measured using the procedure for frequent impulses of Reference [3], the sound level limit at a point of reception within 30 m of a dwelling or a camping area, expressed in terms of the impulse sound level, is 100 dBAI.

9. SOUND LEVEL LIMITS - PEST CONTROL DEVICES

(1) For impulsive sound, other than Quasi-Steady Impulsive Sound, from a pest control device employed solely to protect growing crops, the sound level limit at a point of reception within 30 m of a dwelling or a camping area, expressed in terms of the Logarithmic Mean Impulse Sound Level (L_{LM}), is 70 dBAI.

(2) For sound, including Quasi-Steady Impulsive Sound but not including other impulsive sound, from a pest control device employed solely to protect growing crops, the sound level limit at a point of reception within 30 m of a dwelling or a camping area, expressed in terms of the One Hour Equivalent Sound Level (L_{eq}), is 60 dBA.

10. PROHIBITION - PEST CONTROL DEVICES

The operation of a pest control device employed solely to protect growing crops is prohibited during the hours of darkness, sunset to sunrise.

11. PRE-EMPTION

The least restrictive sound level limit of Sections 8, 9 and 10 applies.

12. EXCLUSION

No restrictions apply to any stationary source resulting in a One Hour Equivalent Sound Level (L_{eq}) or a Logarithmic Mean Impulse Sound Level (L_{LM}), at a point of reception within 30 m of a dwelling or a camping area, lower than the minimum values for that time period, as specified in Table 232-1.

TABLE 232-1
Minimum Values of One Hour L_{eq} or L_{LM} by Time of Day

Time of Day	One Hour L_{eq} (dBA) or L_{LM} (dBAI)
0700 - 1900	45
1900 - 2300	40
2300 - 0700	40

May 21, 1999

Annex to Publication NPC-232
Sound Level Limits for Stationary Sources in Class 3 Areas (Rural)

October 1995

A.1. GENERAL

The definitions in Publication NPC-232 of a Class 3 Area (Rural), as well as Class 1 and 2 Areas (Urban), provide a broad characterization of the areas including a range of localities. In formulating the definitions, consideration was given to the fact that the terms "rural" and "urban" embody a conception of distinct types of dwelling habitat.

On one hand, the term "urban" traditionally conveys a distinct image of a concentration of people and activities in a predominantly man-made environment dominated by road traffic noise, making intensive use of the space available. On the other hand, the term "rural" brings to mind a sparse distribution of people and activities in a predominantly natural environment using land extensively (farming) or not at all (wilderness areas). In between these two categories fall areas that exhibit characteristics of both "urban" and "rural" areas, particularly at different times of the day.

It is, however, evident that not all of the environment will fit neatly into one of these categories. The predominance of road traffic in the area is a significant factor in determining rurality. For example, a residential property in an isolated recreational area, but close to a major roadway, would not be considered to be located in a Class 3 Area.

While examples of a rural setting, described in Publication NPC-232 provide some general guidelines, any classification of a point of reception as being in a Class 1, 2 or 3 Area should be made on an individual basis. The classification can, and should, utilize normally available information on zoning by-laws, official plans, and other policy statements, as well as the future character of the particular piece of land in question and the land in its vicinity.

The standard of environmental noise acceptability for a stationary source is, in general, expressed as the difference between the noise from the source and the background noise. In rural areas, this background noise is formed by natural sounds rather than man-made sounds.

The background noise may also include contributions from existing stationary sources adjacent to the stationary source under impact assessment. Contributions of these secondary stationary noise sources are considered to be a part of the existing noise environment, and may be included in the measurement of the background sound levels, provided that they are not under consideration for noise abatement by the Municipality or the Ministry of Environment and Energy.

In Class 1 and 2 Areas where the acoustical environment is governed primarily by road traffic, the background noise is best described by the energy equivalent sound level (L_{eq}). However, the background noise in Class 3 Areas is often better described in terms of the ninetieth percentile sound level (L_{90}). Therefore, Publication NPC-232 has established both the L_{90} as well as the L_{eq} of the background as the limits against which the intrusion of the source, measured in terms of the L_{eq}, is assessed.

A.2. APPLICATION

Sound level limits contained in this Publication do not apply to non-stationary noise sources nor to any equipment, apparatus or device used in agriculture for food crop seeding, chemical spraying or harvesting. In addition, several specific noise sources have been addressed in separate Publications. Limits for residential air conditioners are contained in Publication NPC-216 - Residential Air Conditioning Devices, Reference [8], and the limits for blasting operations in quarries and surface mines are contained in Publication NPC-119 - Blasting, Reference [7].

A.3. STATIONARY SOURCES

The objective of the definition of a stationary source of sound is to address sources such as industrial and commercial establishments or ancillary transportation facilities. In order to further clarify the scope of the definition, the following list identifies examples of installations, equipment, activities or facilities that are included and those that are excluded as stationary sources.

(1) Included Sources

Individual stationary sources such as:

- Heating, ventilating and air conditioning (HVAC) equipment;
- Rotating machinery;
- Impacting mechanical sources;
- Generators;
- Burners;
- Grain dryers.

Facilities, usually comprising many sources of sound. In this case, the stationary source is understood to encompass all the activities taking place within the property boundary of the facility. The following are examples of such facilities:

- Industrial facilities;
- Commercial facilities;
- Ancillary transportation facilities;
- Aggregate extraction facilities;
- Warehousing facilities;
- Maintenance and repair facilities;
- Snow disposal sites;
- Routine loading and unloading facilities (supermarkets, assembly plants, etc.).

Other sources such as:

- Car washes;
- Race tracks;
- Firearm Ranges.

(2) Excluded Sources

Specific sources or facilities:

- Construction activities;
- Transportation corridors, i.e. roadways and railways;
- Residential air conditioning devices including air conditioners and heat pumps;
- Gas stations;
- Auditory warning devices required or authorized by law or in accordance with good safety practices;
- Occasional movement of vehicles on the property such as infrequent delivery of goods to convenience stores, fast food restaurants, etc.

Other noise sources, normally addressed in a qualitative manner in municipal noise by-laws:

- The operation of auditory signalling devices, including but not limited to the ringing of bells or gongs and the blowing of horns or sirens or whistles, or the production, reproduction or amplification of any similar sounds by electronic means;
- Noise produced by animals kept as domestic pets such as dogs barking;
- Tools and devices used by occupants for domestic purposes such as domestic power tools, radios and televisions, etc., or activities associated with domestic situations such as domestic quarrels, noisy parties, etc;

Noise resulting from gathering of people at facilities such as restaurants and parks.

Activities related to essential service and maintenance of public facilities such as but not limited to roadways, parks and sewers, including snow removal, road cleaning, road repair and maintenance, lawn mowing and maintenance, sewage removal, garbage collection, etc.

A.4. PREDICTABLE WORST CASE IMPACT

The assessment of noise impact requires the determination of the "predictable worst case" impact. The "predictable worst case" impact assessment should establish the largest noise excess produced by the source over the applicable limit. The assessment should reflect a planned and predictable mode of operation of the stationary source.

It is important to emphasize that the "predictable worst case" impact does not necessarily mean that the sound level of the source is highest; it means that the excess over the limit is largest. For example, the excess over the applicable limit at night may be larger even if the day-time sound level produced by the source is higher.

A.5. DEFINITIONS

In the interpretation of Publication NPC-232, the following definitions are of particular relevance:

- Ancillary Transportation Facilities
  "Ancillary transportation facilities" mean subsidiary locations where operations and activities associated with the housing of transportation equipment (or personnel) take place. Examples of ancillary transportation facilities include, but are not limited to, substations, vehicle storage and maintenance facilities, fans, fan and vent shafts, mechanical equipment plants, emergency services buildings, etc;

- Construction
  "Construction" includes erection, alteration, repair, dismantling, demolition, structural maintenance, painting, moving, land clearing, earth moving, grading, excavating, the laying of pipe and conduit whether above or below ground level, street and highway building, concreting, equipment installation and alteration and the structural installation of construction components and materials in any form or for any purpose, and includes any work in connection therewith; "construction" excludes activities associated with the operation at waste and snow disposal sites;

- Construction Equipment
  "Construction equipment" means any equipment or device designed and intended for use in construction, or material handling including but not limited to, air compressors, pile drivers, pneumatic or hydraulic tools, bulldozers, tractors, excavators, trenchers, cranes, derricks, loaders, scrapers, pavers, generators, off-highway haulers or trucks, ditchers, compactors and rollers, pumps, concrete mixers, graders, or other material handling equipment;

- Conveyance
  "Conveyance" includes a vehicle and any other device employed to transport a person or persons or goods from place to place but does not include any such device or vehicle if operated only within the premises of a person;

- Highway
  "Highway" includes a common and public highway, street, avenue, parkway, driveway, square, place, bridge, viaduct or trestle designed and intended for, or used by, the general public for the passage of vehicles;

- Motor Vehicle
  "Motor vehicle" includes an automobile, motorcycle,and any other vehicle propelled or driven otherwise than by muscular power, but does not include the cars of diesel, electric or steam railways, or other motor vehicles running only upon rails, or a motorized snow vehicle, traction engine, farm tractor, self-propelled implement of husbandry or road-building machine within the meaning of the Highway Traffic Act;

- Motorized Conveyance
  "Motorized conveyance" means a conveyance propelled or driven otherwise than by muscular, gravitational or wind power;

- Noise
  "Noise" means unwanted sound;

- Point of Reception - Class 3 Area
  "Point of reception - Class 3 Area" means a point on the premises of a person within 30 m of a dwelling or a camping area, where sound or vibration originating from other than those premises is received.

  For the purpose of approval of new sources, including verifying compliance with Section 9 of the Environmental Protection Act, the point of reception may be located on any of the following existing or zoned for future use premises: permanent or seasonal residences, hotels/motels, nursing/retirement homes, rental residences, hospitals, camp grounds, and noise sensitive buildings such as schools and places of worship.

  For equipment/facilities proposed on premises such as nursing/retirement homes, rental residences, hospitals, and schools, the point of reception may be located on the same premises;

- Stationary Source
  "Stationary source" means a source of sound which does not normally move from place to place and includes the premises of a person as one stationary source, unless the dominant source of sound on those premises is construction or a conveyance;

- Urban Hum
  means aggregate sound of many unidentifiable, mostly road traffic related noise sources.

May 21, 1999

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APPENDIX C

NPC - 205 - SOUND LEVEL LIMITS FOR STATIONARY SOURCES IN CLASS 1 & 2 AREAS (URBAN)

SOUND LEVEL LIMITS FOR STATIONARY SOURCES IN CLASS 1 & 2 AREAS (URBAN)

PUBLICATION NPC-205

OCTOBER 1995

Ontario

Ministry of the Environment

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MINISTRY OF THE ENVIRONMENT

Sound Level Limits for Stationary Sources in Class 1 & 2 Areas (Urban) Publication NPC-205

October 1995

This Publication establishes sound level limits for stationary sources such as industrial and commercial establishments or ancillary transportation facilities, affecting points of reception in Class 1 and 2 Areas (Urban). It replaces Publication NPC-105 "Stationary Sources" of the "Model Municipal Noise Control By-Law, Final Report, August 1978".

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1. SCOPE

This Publication establishes sound level limits for stationary sources such as industrial and commercial establishments or ancillary transportation facilities, affecting points of reception in Class 1 and 2 Areas (Urban). The limits apply to noise complaint investigations carried out in order to determine potential violation of Section 14 of the Environmental Protection Act. The limits also apply to the assessment of planned stationary sources of sound in compliance with Section 9 of the Environmental Protection Act, and under the provisions of the Aggregate Resources Act and the Environmental Assessment Act.

This Publication does not address sound and vibration produced by blasting; blasting in quarries and surface mines is considered in Reference [7].

The Publication includes an Annex, which provides additional details, definitions and rationale for the sound level limits.

2. REFERENCES

Reference is made to the following publications:

[1] NPC-101 - Technical Definitions

[2] NPC-102 - Instrumentation

[3] NPC-103 - Procedures

[4] NPC-104 - Sound Level Adjustments

[6] NPC-206 - Sound Levels due to Road Traffic

[7] NPC-119 - Blasting

[8] NPC-216 - Residential Air Conditioning Devices

[9] NPC-232 - Sound Level Limits for Stationary Sources in Class 3 Areas (Rural)

[10] NPC-233 - Information to be Submitted for Approval of Stationary Sources of Sound

[12] ORNAMENT, Ontario Road Noise Analysis Method for Environment and Transportation, Technical Document, Ontario Ministry of the Environment, ISBN 0-7729-6376, 1989

References [1] to [4] and [7] can be found in the
Model Municipal Noise Control By-Law, Ontario Ministry of the Environment, Final Report, August 1978.

3. TECHNICAL DEFINITIONS

"Ambient sound level"
means Background sound level.

"Background sound level"
is the sound level that is present in the environment, produced by noise sources other than the source under impact assessment. Highly intrusive short duration noise caused by a source such as an aircraft fly-over or a train pass-by is excluded from the determination of the background sound level.

"Class 1 Area"
means an area with an acoustical environment typical of a major population centre, where the background noise is dominated by the urban hum.

"Class 2 Area"
means an area with an acoustical environment that has qualities representative of both Class 1 and Class 3 Areas, and in which a low ambient sound level, normally occurring only between 23:00 and 07:00 hours in Class 1 Areas, will typically be realized as early as 19:00 hours.

Other characteristics which may indicate the presence of a Class 2 Area include:

- absence of urban hum between 19:00 and 23:00 hours;
- evening background sound level defined by natural environment and infrequent human activity; and
- no clearly audible sound from stationary sources other than from those under impact assessment.

"Class 3 Area"
means a rural area with an acoustical environment that is dominated by natural sounds having little or no road traffic, such as the following:

- a small community with less than 1000 population;
- agricultural area;
- a rural recreational area such as a cottage or a resort area; or
- a wilderness area.

Other technical terms are defined in Reference [1] and in the Annex to Publication NPC-205.

4. ESTABLISHMENT OF LIMITS - OBJECTIVE

The sound level limit at a point of reception must be established based on the principle of "predictable worst case" noise impact. In general, the limit is given by the background sound level at the point of reception. The sound level limit must represent the minimum background sound level that occurs or is likely to occur during the operation of the stationary source under impact assessment.

5. BACKGROUND SOUND LEVELS

The time interval between the background sound level measurement and the measurement of the sound level produced by the stationary source under impact assessment should be minimized as much as possible. Preferably, the two measurements should be carried out within one hour of each other.

6. SOUND LEVELS DUE TO STATIONARY SOURCES

(1) Complaint Investigation of Stationary Sources

The One Hour Equivalent Sound Level (L_{eq}) and/or the Logarithmic Mean Impulse Sound Level (L_{LM}) produced by the stationary sources shall be obtained by measurement performed in accordance with Section 7.

(2) Approval of Stationary Sources

The One Hour Equivalent Sound Level (L_{eq}) and/or the Logarithmic Mean Impulse Sound Level (L_{LM}) produced by the stationary sources shall be obtained by measurement or prediction. The estimation of the L_{eq} and/or L_{LM} of the stationary source under impact assessment shall reflect the principle of "predictable worst case" noise impact. The "predictable worst case" noise impact occurs during the hour when the difference between the predicted sound level produced by the stationary source and the background sound level of the natural environment is at a maximum.

7. PROCEDURES

All sound level measurements and calculations shall be made in accordance with References [3], [6]and [12].

Sound from existing adjacent stationary sources may be included in the determination of the background One Hour Equivalent Sound Level (L_{eq}) if such stationary sources of sound are not under consideration for noise abatement by the Municipality or the Ministry of Environment and Energy.

8. SOUND LEVEL LIMITS - GENERAL

(1) For impulsive sound, other than Quasi-Steady Impulsive Sound, from a stationary source, the sound level limit expressed in terms of the Logarithmic Mean Impulse Sound Level (L_{LM}) is the background One Hour Equivalent Sound Level (L_{eq}) typically caused by road traffic as obtained pursuant to Section 6 for that point of reception.

(2) For sound from a stationary source, including Quasi-Steady Impulsive Sound but not including other impulsive sound, the sound level limit expressed in terms of the One Hour Equivalent Sound Level (L_{eq}) is the background One Hour Equivalent Sound Level (L_{eq}) typically caused by road traffic as obtained pursuant to Section 6 for that point of reception.

9. SOUND LEVEL LIMITS - SPECIFIC IMPULSIVE SOUNDS

(1) For impulsive sound, other than Quasi-Steady Impulsive Sound, from a stationary source which is an industrial metal working operation (including but not limited to forging, hammering, punching, stamping, cutting, forming and moulding), the sound level limit at a point of reception expressed in terms of the Logarithmic Mean Impulse Sound Level (L_{LM}) is 60 dBAI, if the stationary source were operating before January 1, 1980, and otherwise is 50 dBAI.

(2) For impulsive sound, other than Quasi-Steady Impulsive Sound, from a stationary source which is the discharge of firearms on the premises of a licensed gun club, the sound level limit at a point of reception expressed in terms of the Logarithmic Mean Impulse Sound Level (L_{LM}) is:

- 70 dBAI if the gun club were operating before January 1, 1980; or
- 50 dBAI if the gun club began to operate after January 1, 1980; or
- the L_{LM} prior to expansion, alteration or conversion.

(3) For impulsive sound, other than Quasi-Steady Impulsive Sound, from a stationary source which is not a blasting operation in a surface mine or quarry, characterized by impulses which are so infrequent that they cannot normally be measured using the procedure for frequent impulses of Reference [3] the sound level limit at a point of reception expressed in terms of the impulse sound level is 100 dBAI.

10. SOUND LEVEL LIMITS - PEST CONTROL DEVICES

(1) For impulsive sound, other than Quasi-Steady Impulsive Sound, from a pest control device employed solely to protect growing crops, the sound level limit at a point of reception expressed in terms of the Logarithmic Mean Impulse Sound Level (L_{LM}) is 70 dBAI.

(2) For sound, including Quasi-Steady Impulsive Sound but not including other impulsive sound, from a pest control device employed solely to protect growing crops, the sound level limit at a point of reception expressed in terms of the One Hour Equivalent Sound Level (L_{eq}) is 60 dBA.

11. PROHIBITION - PEST CONTROL DEVICES

The operation of a pest control device employed solely to protect growing crops outdoors during the hours of darkness, sunset to sunrise, is prohibited.

12. PRE-EMPTION

The least restrictive sound level limit of Sections 8, 9 and 10 applies.

13. EXCLUSION

No restrictions apply to a stationary source resulting in a One Hour Equivalent Sound Level (L_{eq}) or a Logarithmic Mean Impulse Sound Level (L_{LM}) lower than the minimum values for that time period specified in Table 205-1.

TABLE 205-1

Minimum Values of One Hour L_{eq} or L_{LM} by Time of Day

	One Hour L_{eq} (dBA) or L_{LM} (dBAI)	
Time of Day	Class 1 Area	Class 2 Area
0700 - 1900	50	50
1900 - 2300	47	45
2300 - 0700	45	45

May 21, 1999

Annex to Publication NPC-205
Sound Level Limits for Stationary Sources in Class 1 & 2 Areas (Urban)

October 1995

A.1. GENERAL

In general, noises are annoying because they are heard over and above the level of the so-called "background" or surrounding environmental noise climate at a particular location. The standard for environmental noise acceptability of stationary sources is therefore expressed as the difference between noise from the source and the background noise.

The background noise is essentially made up of the road traffic noise which creates an "urban hum". It may also include contributions from existing industry or commercial activity adjacent to the stationary source under investigation. Contributions of these secondary noise sources are considered to be a part of urban hum and may be included in the measurements or calculation of the background sound levels, provided that they are not under consideration for noise abatement by the Municipality or the Ministry of Environment and Energy.

The sound level limits specified in Section 8 of Publication NPC-205 represent the general limitation on noise produced by stationary sources. Some noises, however, are annoying no matter where or in what kind of environment they exist. High level impulsive noises represent a special category and, consequently, are restricted by an absolute limitation. Sections 9 and 10 of this Publication provide criteria of acceptability for specific impulsive noise sources.

A.2. APPLICATION

The limits presented in Publication NPC-205 are designed for the control of noise from sources located in industrial, commercial or residential areas. The limits apply to points of reception located in Class 1 and Class 2 Areas.

Sound level limits contained in Publication NPC-205 do not apply to the excluded noise sources listed in Section A.3.(2) and neither do they apply to any equipment, apparatus or device used in agriculture for food crop seeding, chemical spraying or harvesting. In addition, several specific noise sources have been addressed in separate Publications. Limits for residential air conditioners are contained in Publication NPC-216 - Residential Air Conditioning Devices, Reference [8] and the limits for blasting operations in quarries and surface mines are contained in Publication NPC-119 - Blasting, Reference [7].

A.3. STATIONARY SOURCES

The objective of the definition of a stationary source of sound is to address sources such as industrial and commercial establishments or ancillary transportation facilities. In order to further clarify the scope of the definition, the following list identifies examples of installations, equipment, activities or facilities that are included and those that are excluded as stationary sources.

(1) Included Sources

Individual stationary sources such as:

- Heating, ventilating and air conditioning (HVAC) equipment;
- Rotating machinery;
- Impacting mechanical sources;
- Generators;
- Burners;
- Grain dryers.

Facilities, usually comprising many sources of sound. In this case, the stationary source is understood to encompass all the activities taking place within the property boundary of the facility. The following are examples of such facilities:

- Industrial facilities;
- Commercial facilities;
- Ancillary transportation facilities;
- Aggregate extraction facilities;
- Warehousing facilities;
- Maintenance and repair facilities;
- Snow disposal sites;
- Routine loading and unloading facilities (supermarkets, assembly plants, etc.).

Other sources such as:

- Car washes;
- Race tracks;
- Firearm Ranges.

(2) Excluded Sources

Secific sources or facilities:

- Construction activities;
- Transportation corridors, i.e. roadways and railways;
- Residential air conditioning devices including air conditioners and heat pumps;
- Gas stations;
- Auditory warning devices required or authorized by law or in accordance with good safety practices;
- Occasional movement of vehicles on the property such as infrequent delivery of goods to convenience stores, fast food restaurants, etc.

Other noise sources, normally addressed in a qualitative manner in municipal noise by-laws:

- The operation of auditory signalling devices, including but not limited to the ringing of bells or gongs and the blowing of horns or sirens or whistles, or the production, reproduction or amplification of any similar sounds by electronic means;
- Noise produced by animals kept as domestic pets such as dogs barking;
- Tools and devices used by occupants for domestic purposes such as domestic power tools, radios and televisions, etc., or activities associated with domestic situations such as domestic quarrels, noisy parties, etc;
- Noise resulting from gathering of people at facilities such as restaurants and parks.

Activities related to essential service and maintenance of public facilities such as but not limited to roadways, parks and sewers, including snow removal, road cleaning, road repair and maintenance, lawn mowing and maintenance, sewage removal, garbage collection, etc.

A.4. PREDICTABLE WORST CASE IMPACT

The assessment of noise impact requires the determination of the "predictable worst case" impact. The "predictable worst case" impact assessment should establish the largest noise excess produced by the source over the applicable limit. The assessment should reflect a planned and predictable mode of operation of the stationary source.

It is important to emphasize that the "predictable worst case" impact does not necessarily mean that the sound level of the source is highest; it means that the excess over the limit is largest. For example, the excess over the applicable limit at night may be larger even if the day-time sound level produced by the source is higher.

A.5. DEFINITIONS

In the interpretation of Publication NPC-205, the following definitions are of particular relevance:

- Ancillary Transportation Facilities
  "Ancillary transportation facilities" mean subsidiary locations where operations and activities associated with the housing of transportation equipment (or personnel) take place. Examples of ancillary transportation facilities include, but are not limited to, substations, vehicle storage and maintenance facilities, fans, fan and vent shafts, mechanical equipment plants, emergency services buildings, etc;

- Construction
  "Construction" includes erection, alteration, repair, dismantling, demolition, structural maintenance, painting, moving, land clearing, earth moving, grading, excavating, the laying of pipe and conduit whether above or below ground level, street and highway building, concreting, equipment installation and alteration and the structural installation of construction components and materials in any form or for any purpose, and includes any work in connection therewith; "construction" excludes activities associated with the operation at waste and snow disposal sites;

- Construction Equipment
  "Construction equipment" means any equipment or device designed and intended for use in construction, or material handling including but not limited to, air compressors, pile drivers, pneumatic or hydraulic tools, bulldozers, tractors, excavators, trenchers, cranes, derricks, loaders, scrapers, pavers, generators, off-highway haulers or trucks, ditchers, compactors and rollers, pumps, concrete mixers, graders, or other material handling equipment;

- Conveyance
  "Conveyance" includes a vehicle and any other device employed to transport a person or persons or goods from place to place but does not include any such device or vehicle if operated only within the premises of a person;

- Highway
  "Highway" includes a common and public highway, street, avenue, parkway, driveway, square, place, bridge, viaduct or trestle designed and intended for, or used by, the general public for the passage of vehicles;

- Motor Vehicle
  "Motor vehicle" includes an automobile, motorcycle,and any other vehicle propelled or driven otherwise than by muscular power, but does not include the cars of diesel, electric or steam railways, or other motor vehicles running only upon rails, or a motorized snow vehicle, traction engine, farm tractor, self-propelled implement of husbandry or road-building machine within the meaning of the Highway Traffic Act;

- Motorized Conveyance
  "Motorized conveyance" means a conveyance propelled or driven otherwise than by muscular, gravitational or wind power;

- Noise
  "Noise" means unwanted sound;

- Point of Reception
  "Point of reception" means any point on the premises of a person where sound or vibration originating from other than those premises is received.

For the purpose of approval of new sources, including verifying compliance with Section 9 of the Environmental Protection Act, the point of reception may be located on any of the following existing or zoned for future use premises: permanent or seasonal residences, hotels/motels, nursing/retirement homes, rental residences, hospitals, camp grounds, and noise sensitive buildings such as schools and places of worship.

For equipment/facilities proposed on premises such as nursing/retirement homes, rental residences, hospitals, and schools, the point of reception may be located on the same premises;

- Stationary Source
  "Stationary source" means a source of sound which does not normally move from place to place and includes the premises of a person as one stationary source, unless the dominant source of sound on those premises is construction or a conveyance;

- Urban Hum
  means aggregate sound of many unidentifiable, mostly road traffic related noise sources.

May 21, 1999

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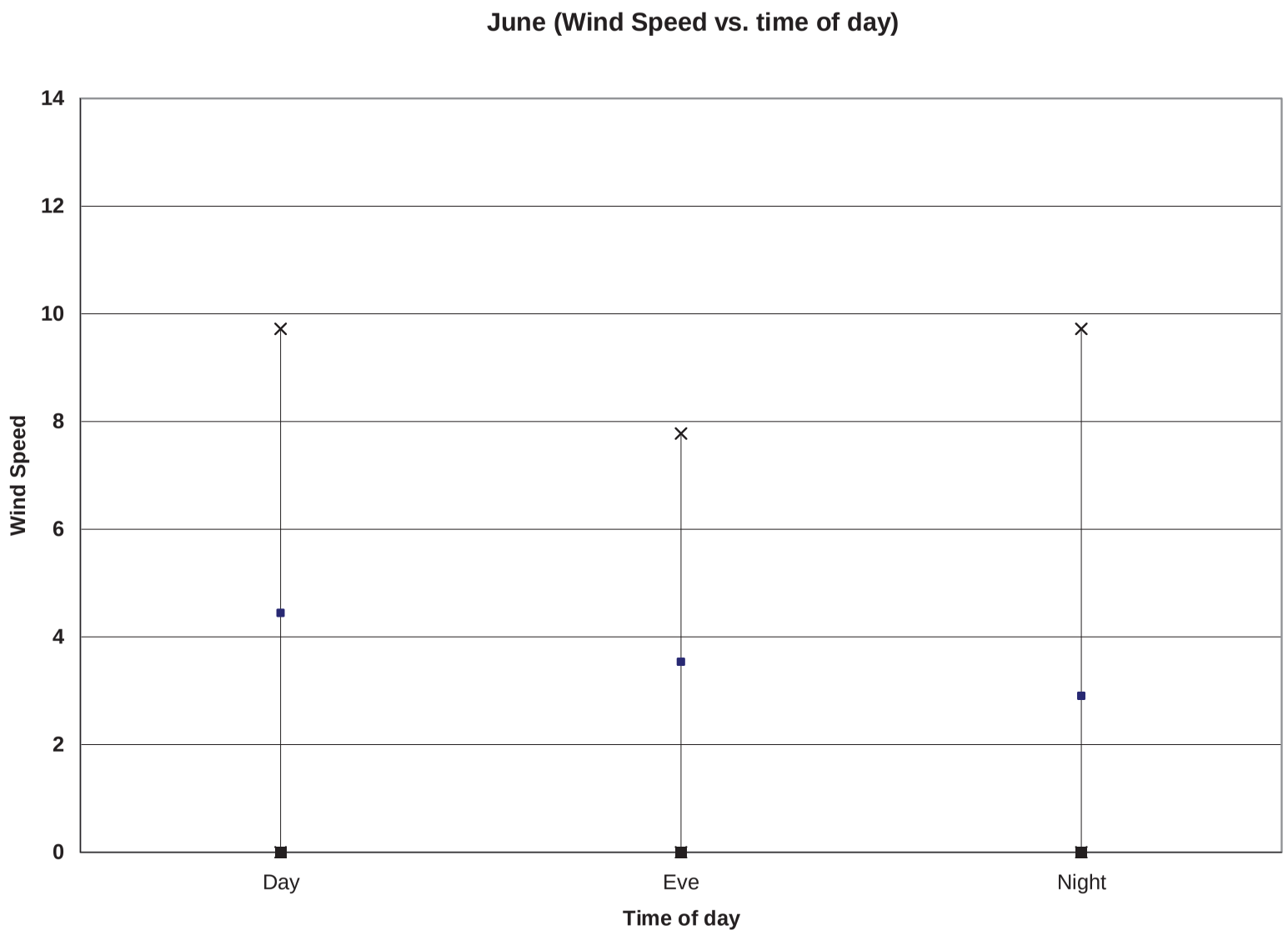
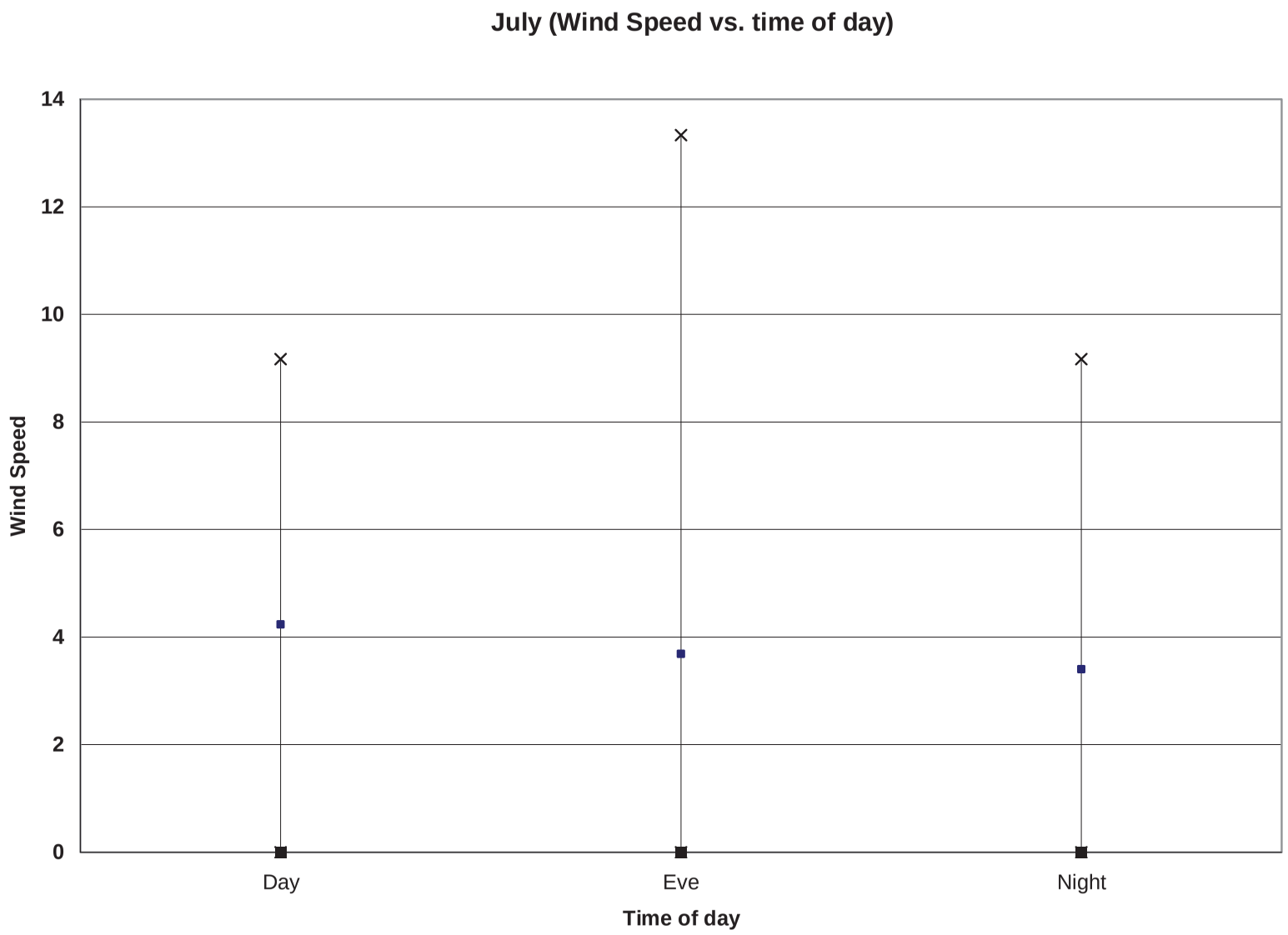
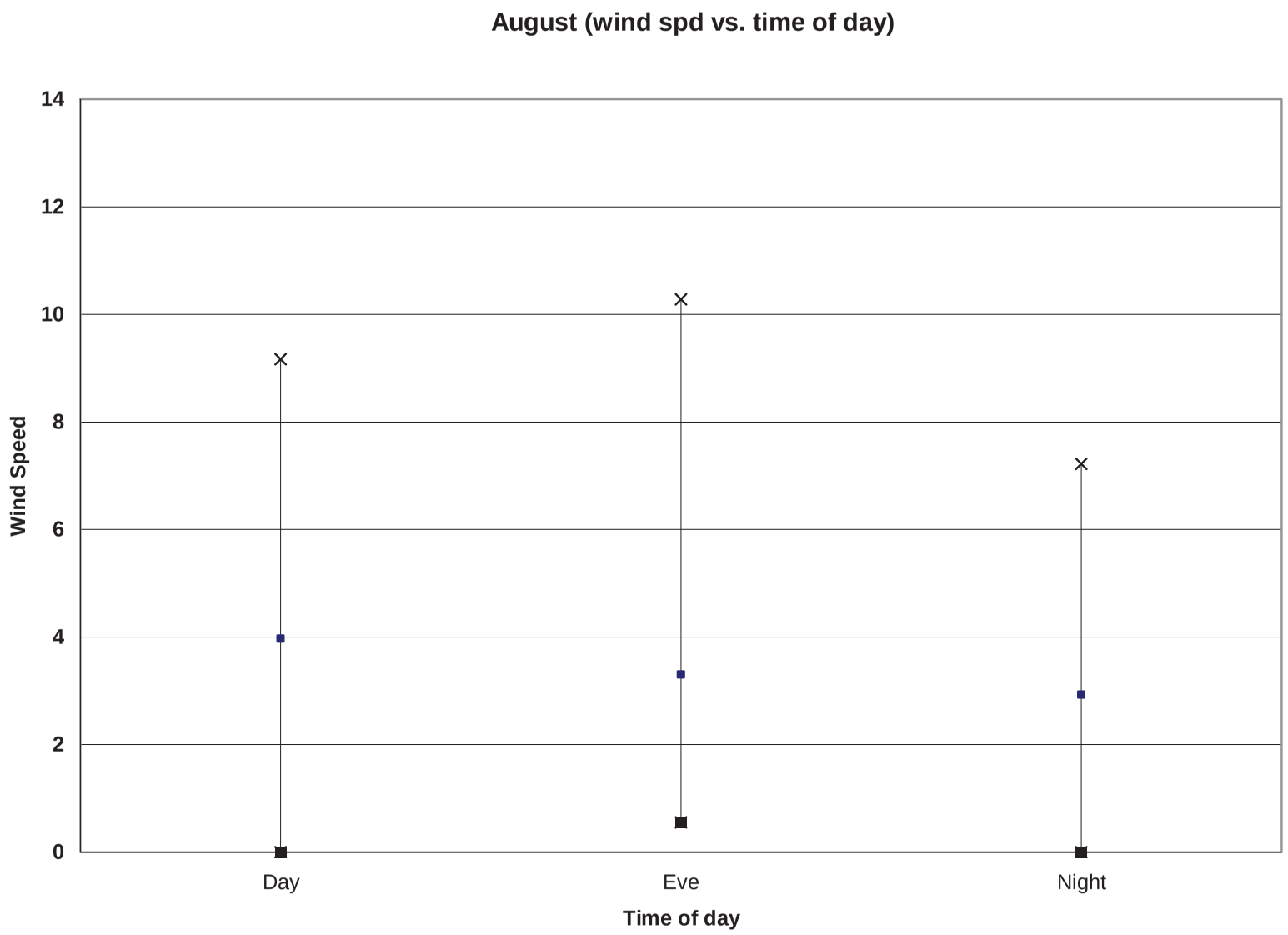
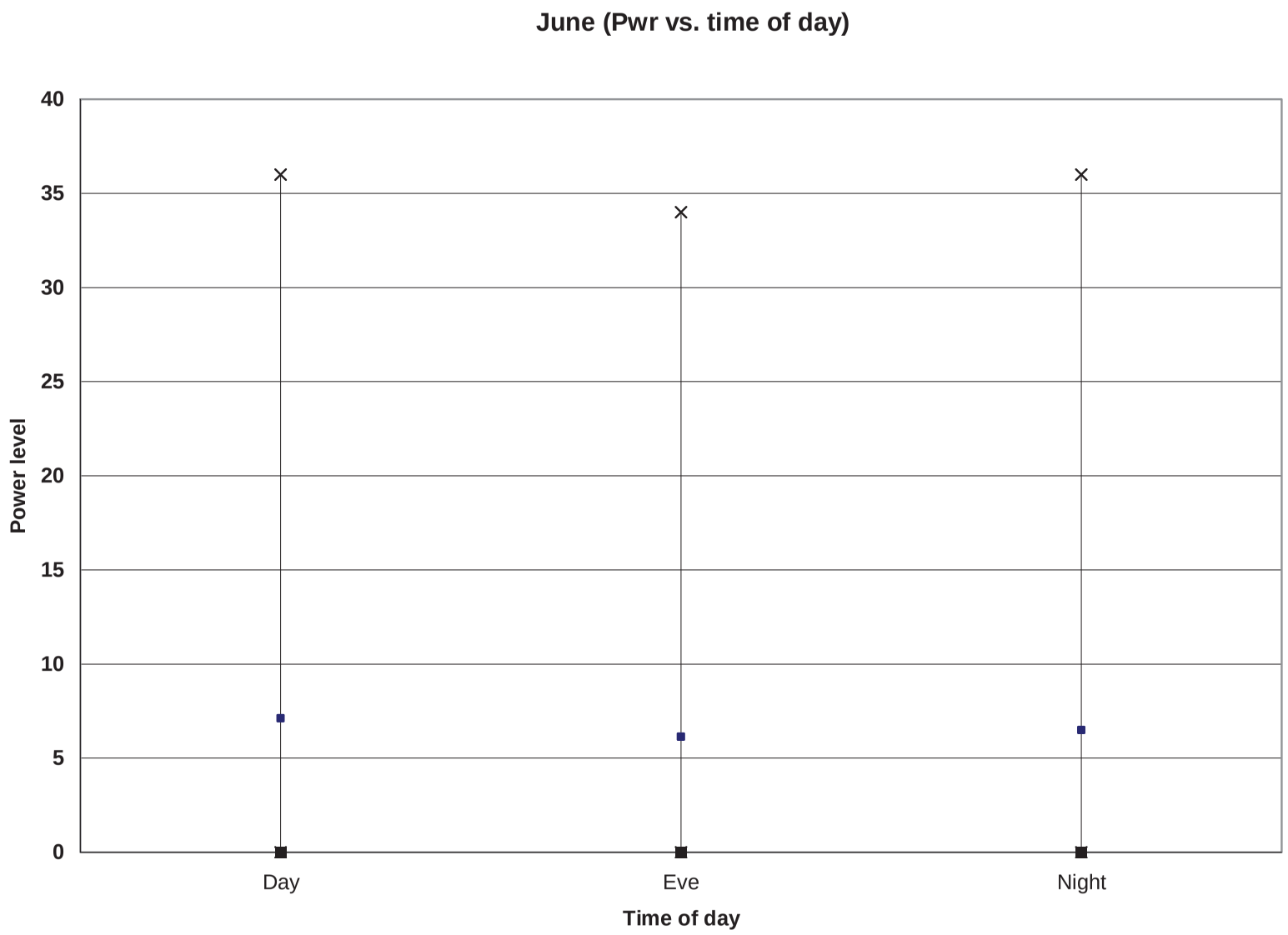
APPENDIX D

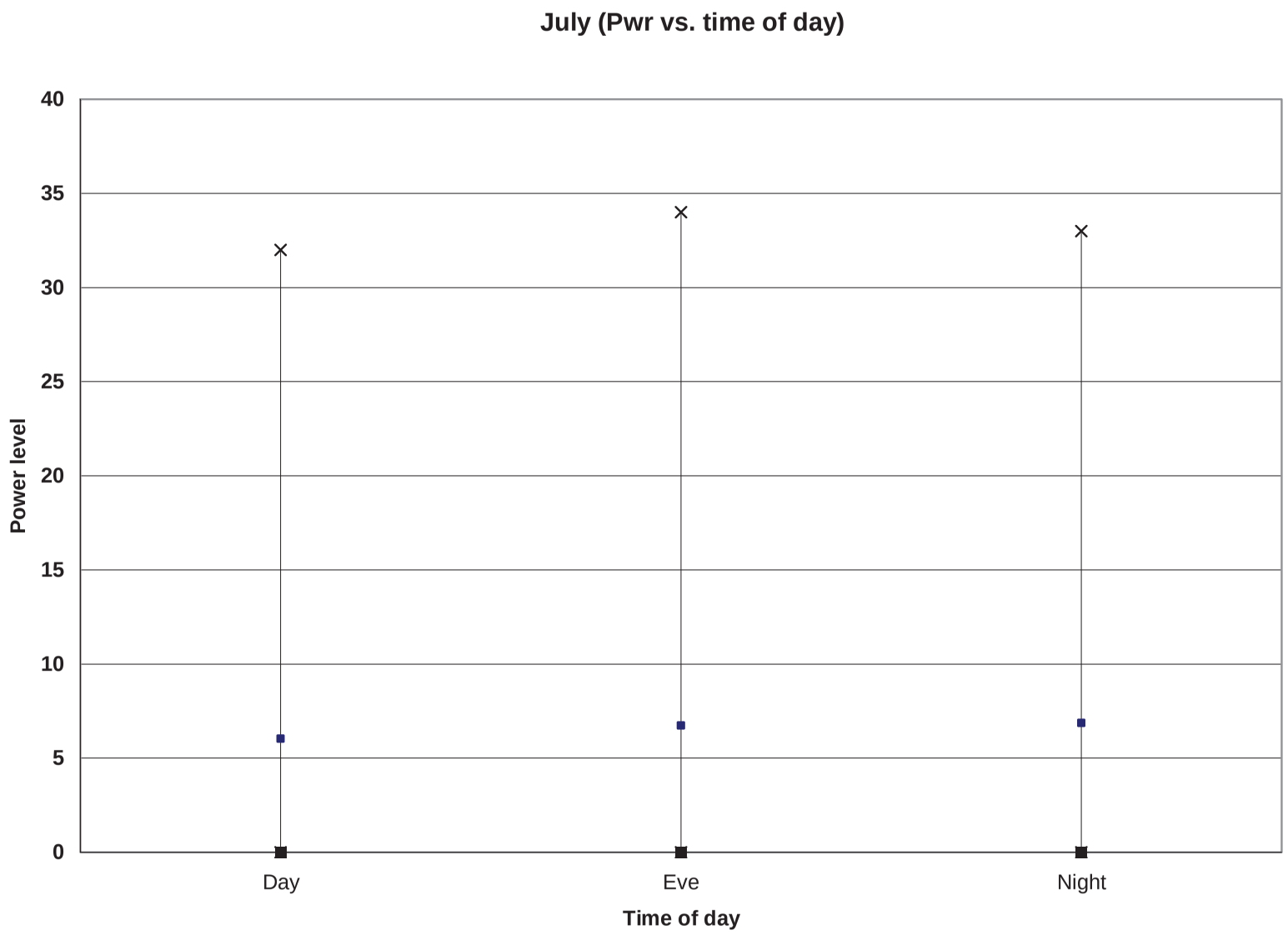
WEATHER DATA (GODERICH STATION) - WIND POWER OUTPUT DATA (KINGSBRIDGE WIND FARMS) FOR JUNE, JULY & AUGUST 2006

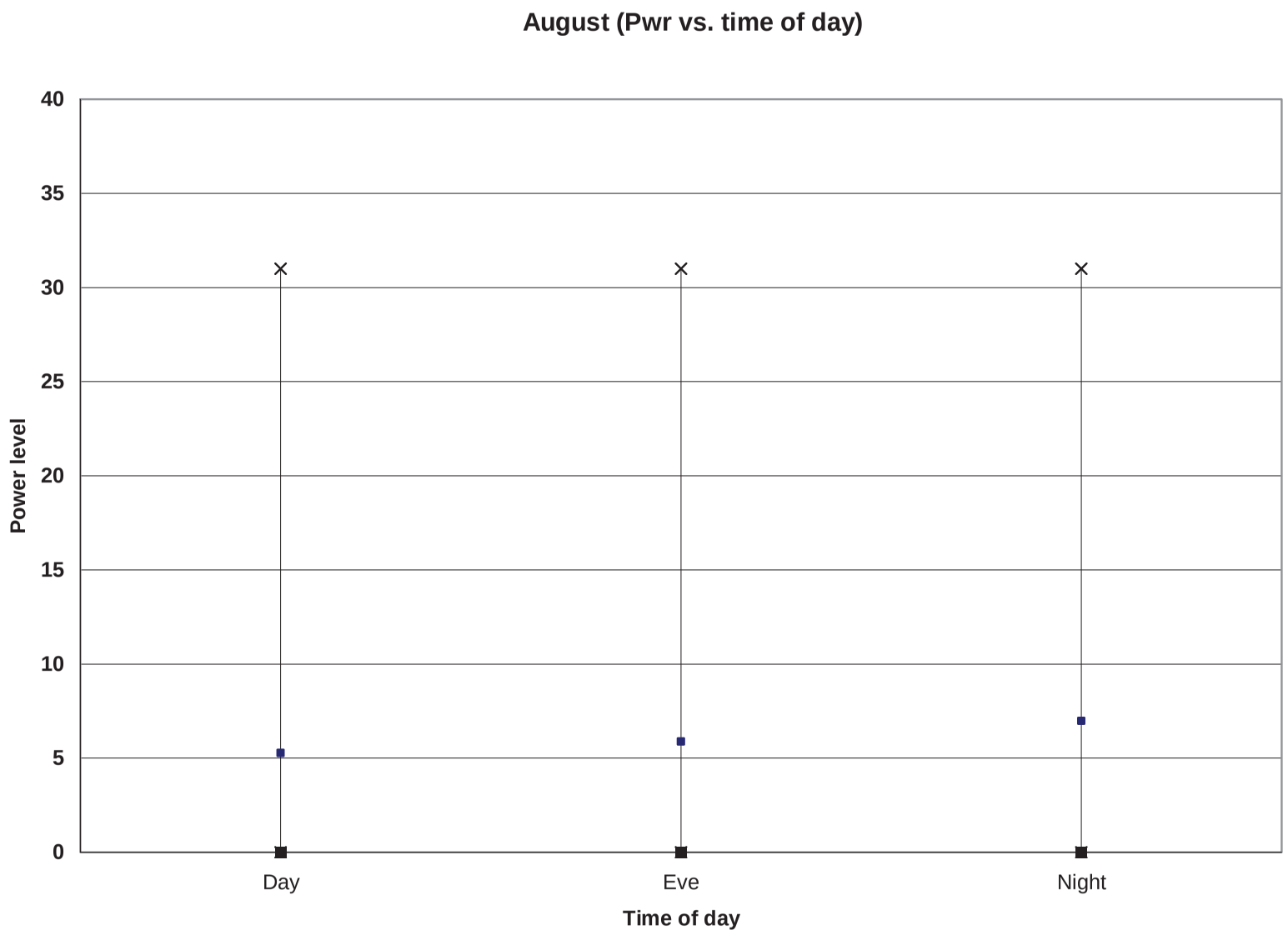

June (Wind Speed vs. time of day)
14
12
10
8
6
4
2
0
Wind Speed
Day
Eve
Night
Time of day

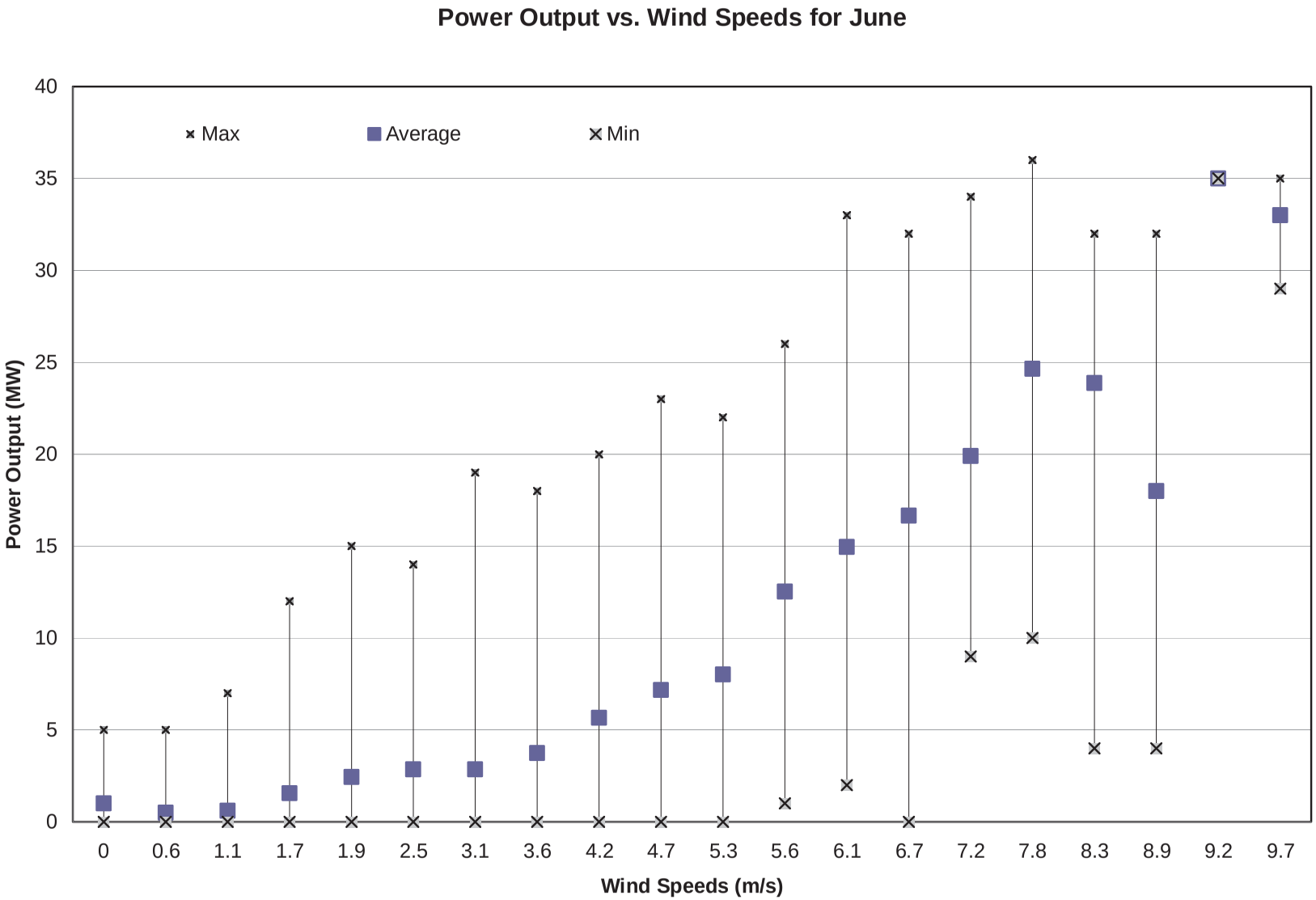

July (Wind Speed vs. time of day)
14
12
10
8
6
4
2
0
Wind Speed
Day
Eve
Night
Time of day

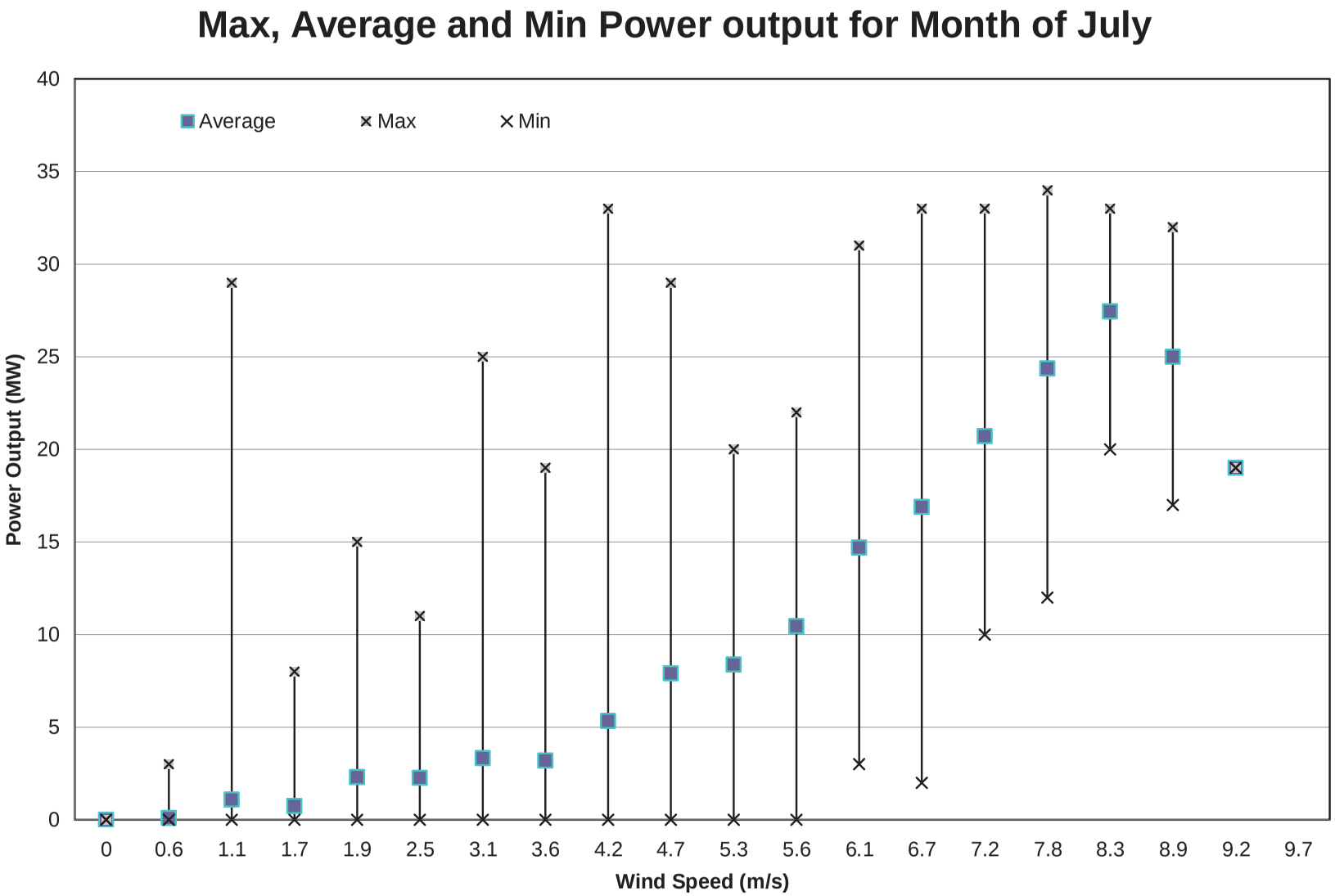

August (wind spd vs. time of day)
14
12
10
8
6
4
2
0
Wind Speed
Day
Eve
Night
Time of day

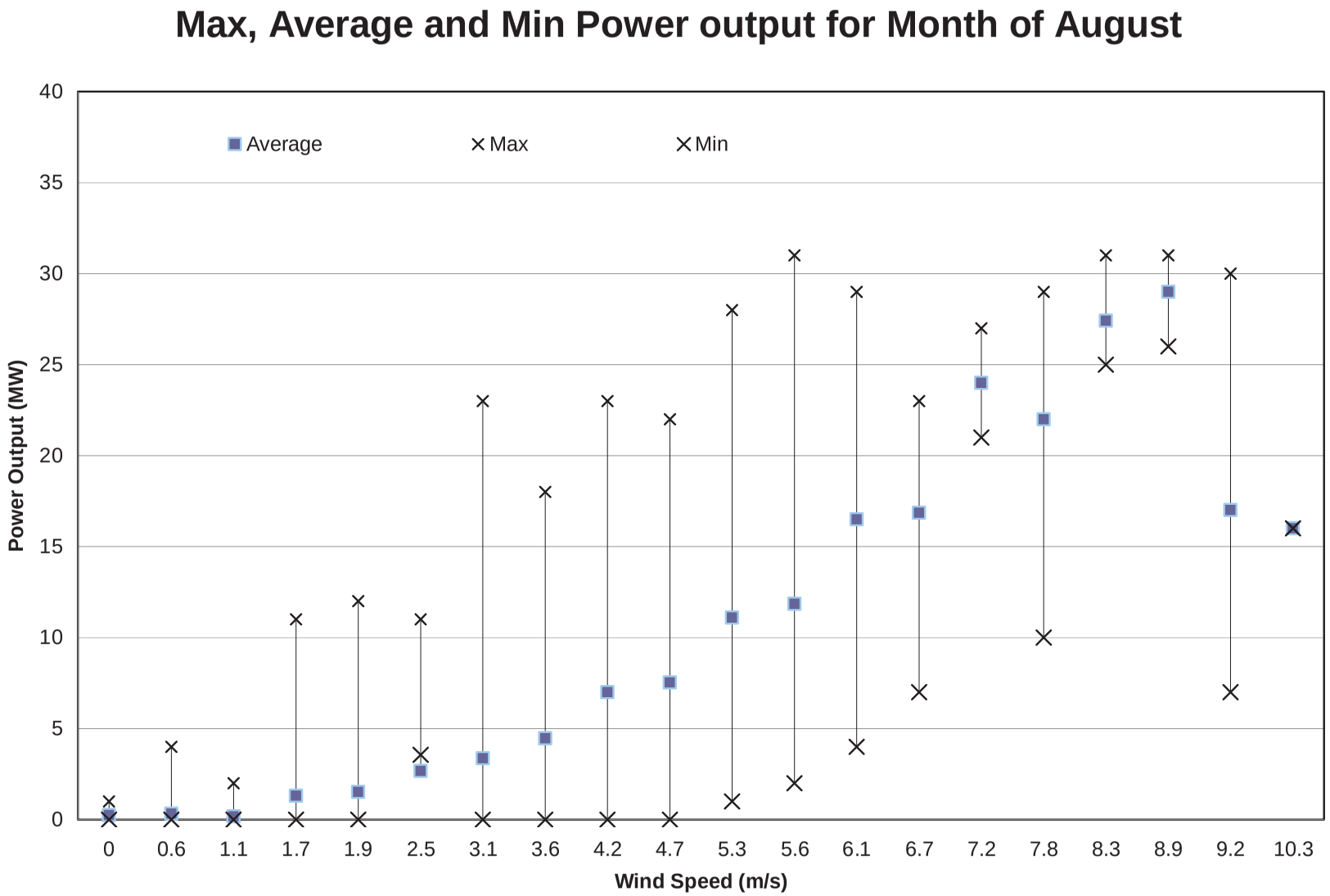

June (Pwr vs. time of day)
40
35
30
25
20
15
10
5
0
Power level
Day
Eve
Night
Time of day


July (Pwr vs. time of day)
40
35
30
25
20
15
10
5
0
Power level
Day
Eve
Night
Time of day

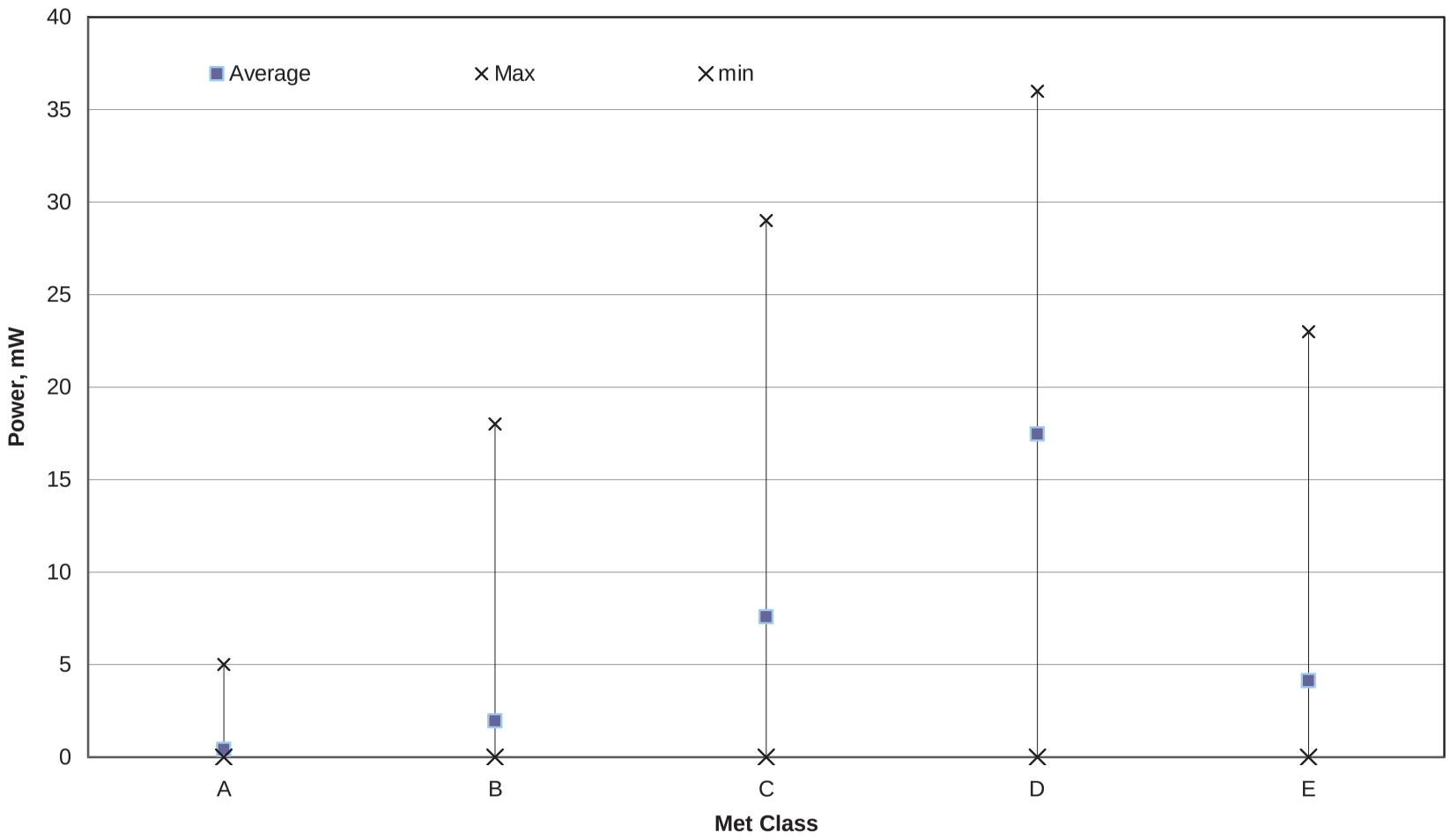

August (Pwr vs. time of day)
40
35
30
25
20
15
10
5
0
Power level
Day
Eve
Night
Time of day


Power Output vs. Wind Speeds for June
Max
Average
Min
Power Output (MW)
40
35
30
25
20
15
10
5
0
0
0.6
1.1
1.7
1.9
2.5
3.1
3.6
4.2
4.7
5.3
5.6
6.1
6.7
7.2
7.8
8.3
8.9
9.2
9.7
Wind Speeds (m/s)

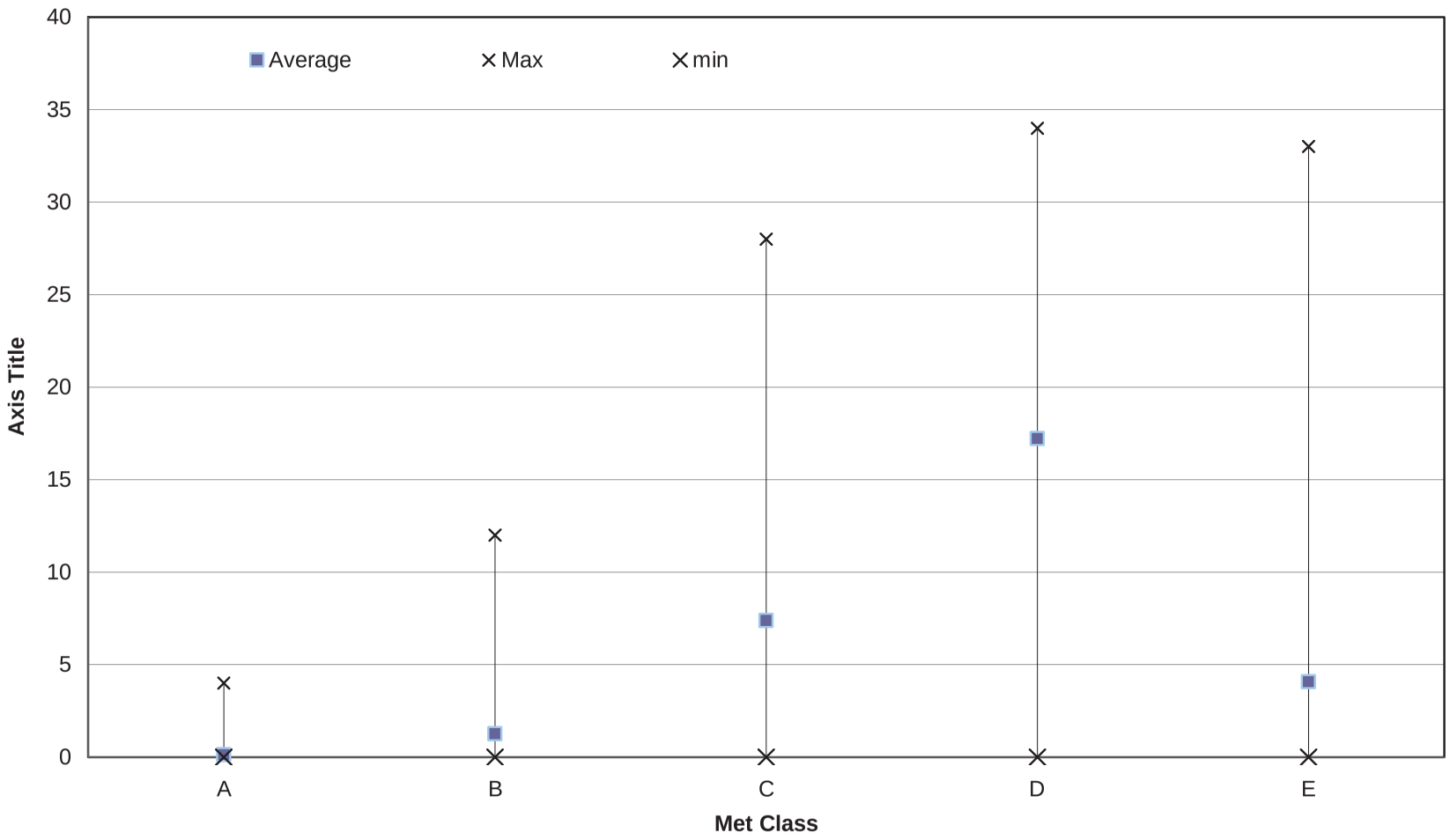

Max, Average and Min Power output for Month of July
Average
Max
Min
Power Output (MW)
40
35
30
25
20
15
10
5
0
0
0.6
1.1
1.7
1.9
2.5
3.1
3.6
4.2
4.7
5.3
5.6
6.1
6.7
7.2
7.8
8.3
8.9
9.2
9.7
Wind Speed (m/s)


Max, Average and Min Power output for Month of August
Average
Max
Min
Power Output (MW)
40
35
30
25
20
15
10
5
0
0
0.6
1.1
1.7
1.9
2.5
3.1
3.6
4.2
4.7
5.3
5.6
6.1
6.7
7.2
7.8
8.3
8.9
9.2
10.3
Wind Speed (m/s)

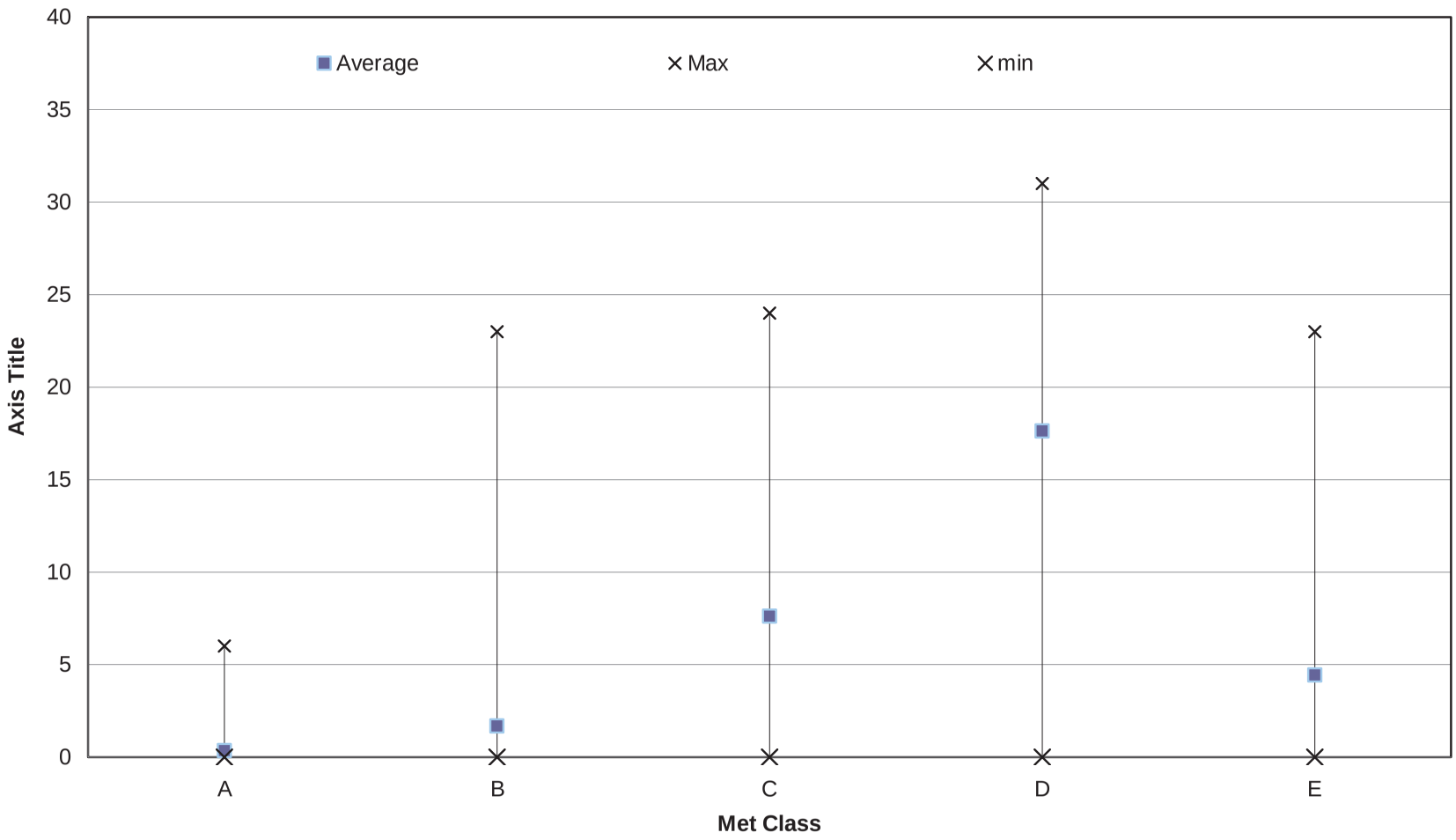
Max, Average and Min Power output for Month of June vs. Class

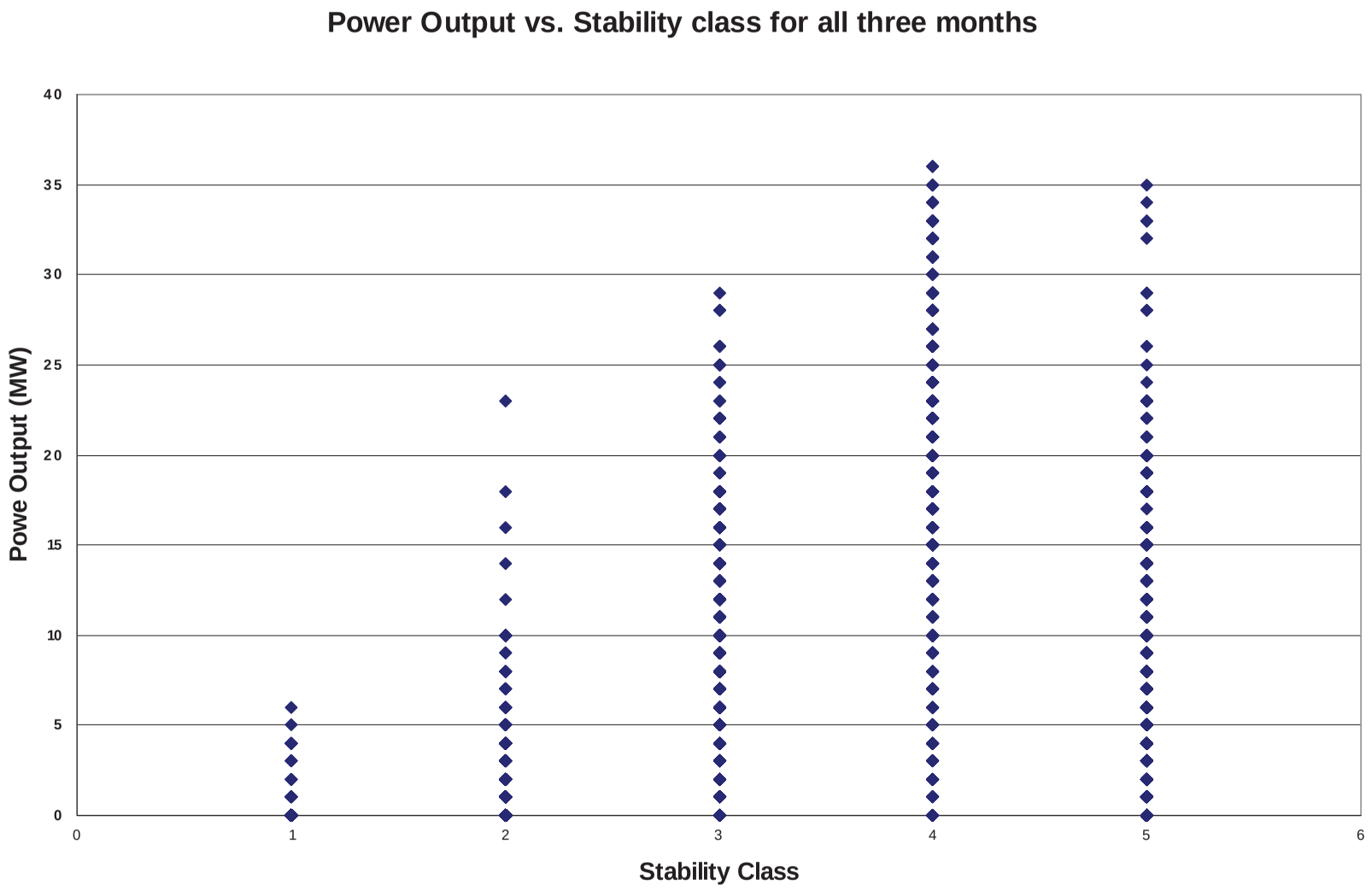


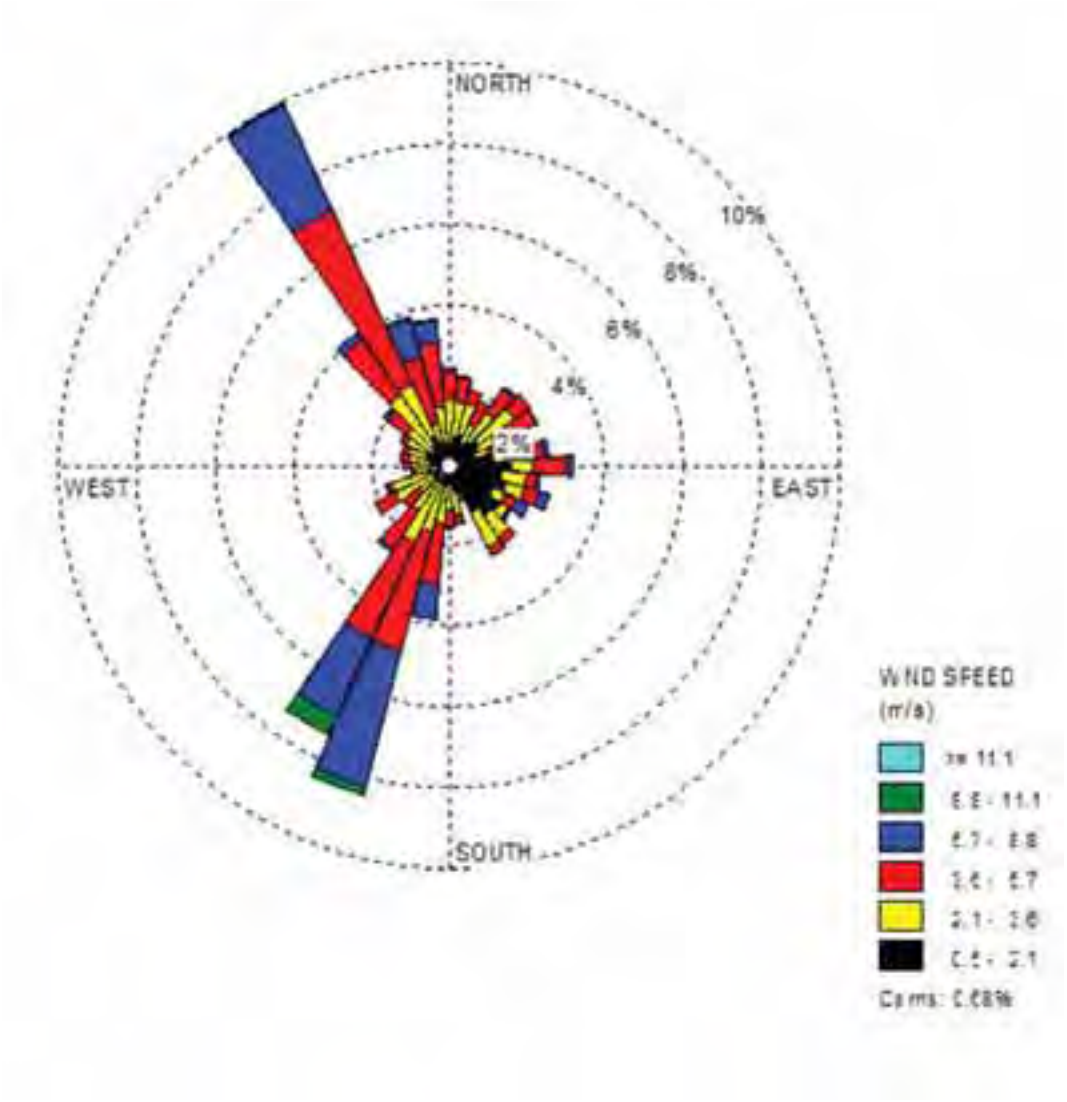
Max, Average and Min Power output for Month of July vs. Class



Max, Average and Min Power output for Month of August vs. Class




Power Output vs. Stability class for all three months
Powe Output (MW)
40
35
30
25
20
15
10
5
0
0
1
2
3
4
5
6
Stability Class



Windrose data for Goderich Station for June, July and August 2006 combined.

APPENDIX E

THE BEATING PHENOMENON

E1. Background

One of the main source characteristics that has been attributed to wind turbine noise is they produce swishing sound. Alternate terminologies used for the swishing sound are; beating, thumping, hammer etc. etc. by people being exposed to the wind turbine noise.

G. P. van den berg in his doctoral dissertation, Chapter V-Page 61 (Reference 1) states, "Atmospheric stability is not only relevant for wind turbine sound *levels*, as we saw in he preceding chapter, but also for the *character* of the sound. In conditions where the atmosphere is stable, distant wind turbines can produce a beating or thumping sound that is not apparent in daytime."

A brief introduction is given in this appendix on the beating phenomenon in acoustics. Some salient points such as 'tuning process in music' as well as 'the subjective reaction' to beating are also highlighted. Clarification for beating in wind turbine noise is also given in this appendix and attempts will also be made to distinguish the 'swishing' phenomenon from 'the beating' phenomenon.

Two references are used extensively while preparing this appendix and are:

E1) *Fundamentals of Acoustics* by L. E. Kinsler and A. R. Frey, Second Edition, John Wiley & Sons, Inc. 1962. ISBN 0 471 46049 5; and

E2) Musical Acoustics – An Introduction by D. E. Hall, Wadsworth Publishing Co. 1980. ISBN 0-534-00758-9.

E2. Beats

A simple scientific definition of 'Beating' is: "the linear combination of two simple harmonic vibrations of nearly the same frequency results in the *phenomenon* of *beats*."

Without any loss of generality, each of the vibrating wave can be represented by,

$$Wave_1 = A_1 \sin(f_1 t) \quad \text{and} \quad Wave_2 = A_2 \sin(f_2 t) \qquad \text{(E1)}$$

Where, A_1 and A_2 are amplitudes of the two waves and f_1 and f_2 are the frequencies of the two the two waves. When the two waves are summed together, (i.e.) played together, the resulting vibration can be regarded as approximately simple harmonic, with a frequency that lies somewhere between f_1 and f_2 and the amplitude varying slowly at a frequency of $(f_1 – f_2)$ and we have assumed that f_1 is larger than f_2. The amplitude of the combined wave will 'wax' and 'wane' between the two limits $(A_1 + A_2)$ and $(A_1 - A_2)$.

In the case of sound waves, the simultaneous sounding of two pure tones of slightly different frequency, the above variation in amplitude results in a rhythmic pulsing of the loudness of the sound which occurs at a rate corresponding to the difference in frequency, $(f_1 – f_2)$, of the two sounds and is known as *beating*. Audible beats are heard whenever two sound of nearly the same frequency strike the ear, and when the frequency of each component is within the audible range. If the frequency difference is small, about 10 or less cycles per sec, the resulting sound waxes and wanes at this rate, with an apparent pitch corresponding to the average frequency. If, on the other hand, their frequency difference is about 200 cycles per sec or more, a combination tone may be observed whose frequency is equal to the difference between that of the two sounds. For intermediate frequency differences, the sound has a rough and discordant character.

A graphical representation of the onset and disappearance of the *beating* phenomenon is highlighted through a series of plots generated from two sounds and are shown in Figures E1 through E7 below.

Figure E1. The Beat Phenemenon

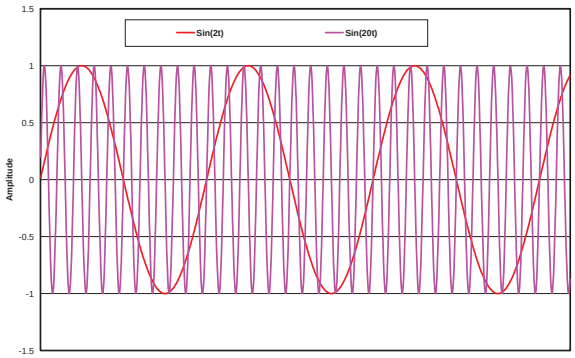


Figure E2. The Beat Phenemenon

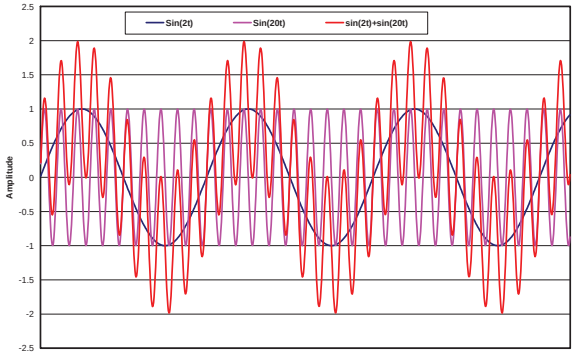


Figure E3. The Beat Phenemenon

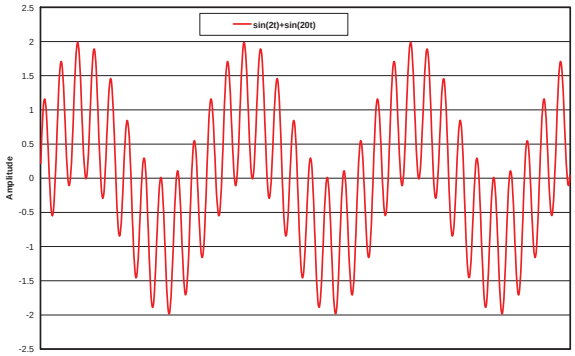


Figure E4. The Beat Phenemenon

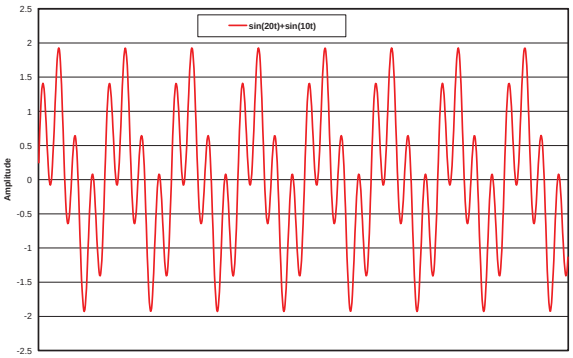


Figure E5. The Beat Phenemenon

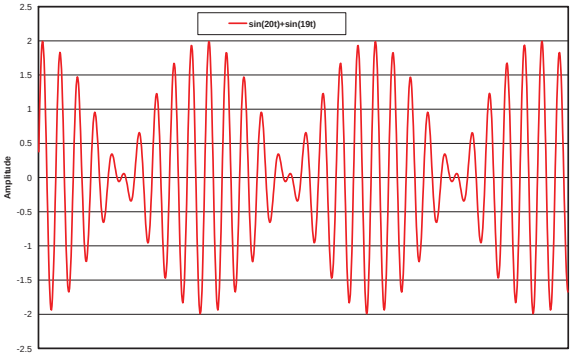


Figure E6. The Beat Phenemenon

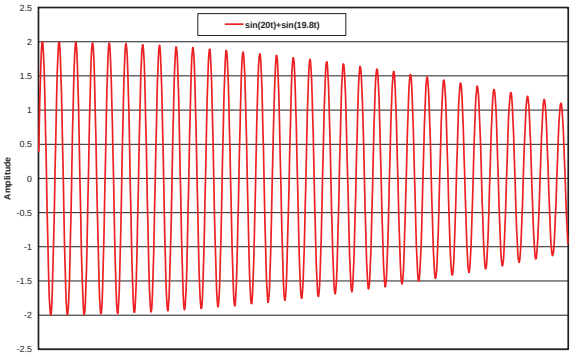


Figure E7. The Beat Phenemenon

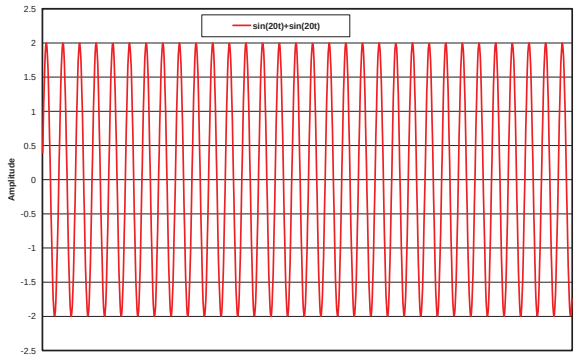


Figure E1 shows two simple sound waves at frequencies of 2 and 20 cycles per second, with their sum shown in Figure E2. One can see frequencies 2 and 20 as well as the beat frequency of 18. The *beat* is not as pronounced since the beat rate is close to the frequency of one of the two sounds as seen in Figure E3. The difference in the two frequencies is 10 in the 'beating' shown in Figure E4. The true 'beating' is not clear in Figure E4 since the beating rate is 10. Figures E5 and E6 show true *beat*. The amplitude is changing between 0 and 1 at a beat rate of 1 and 0.2.

E3. Subjective Response

If the sounds are within audible range, the resulting sound is heard as a single sound whose loudness varies smoothly and rhythmically at the beat rate, and it is said that the sounds *beat* with each other. Actually, the beating phenomenon is used by musical instrument tuners to tune, precisely by observing the beating and adjust for "zero" beat.

The main subjective effect of the 'beating phenomenon' is that the resulting sound appears harsh and discordant. The level of such a response is based on the beat rate as well as the level of the sound. At low levels of the sound, say less than 50 to 60 dB, the only effect is that waxing and waning of the sound.

APPENDIX F

AN ASSESSMENT PROCEDURE

F1. Background

One of the main concerns with the assessment procedures used by different jurisdictions, except New Zealand, is that the effects of meteorological conditions were not appropriately accounted for. Even the New Zealand approach accounts for the effect of wind shear by applying the wind speed data at each site, measured at the hub-height.

It was stated earlier that the current procedures in Ontario are very simple to apply and were similar to other jurisdiction in Europe. The procedure does not require the establishment of ambient sound levels at affected receptor locations before the installation of the wind farm. Neither is there a requirement to incorporate the prevailing meteorological conditions at the proposed wind farm site. Below is an example of one possible assessment process that could address the above concerns. Additional research and analysis would be required in order to develop an appropriate assessment process.

i. Following the standard procedures used in New Zealand, the ambient sound levels are to be monitored for a pre-set time, say for a month, at salient points of reception. The data should be collected in intervals of 10 minutes so as to be able to evaluate statistically valid analysis;
ii. The prevailing weather conditions, wind speed, direction, stability class are also measured at the wind farm site for the same duration and time intervals;
iii. The meteorological data is collected at a minimum of two heights (say 10 m and at hub-height);
iv. The analysis would involve correlation between wind profiles, determination of shear coefficients (similar to the schemes reported in Reference 22), support for the argument of hub-height wind speeds;
v. The noise prediction models, for the proposed wind farm, will include the effect of dominant scenarios of meteorological conditions and evaluate the potential range of noise levels;

vi. One would then assign suitable assessment conditions, based on appropriate statistical parameters, for the range of noise levels that can be expected at the salient points of receptions. Some preliminary concepts of this are:

a) Establish the noise levels at all salient receptor locations by applying the current MOE procedures;
b) Establish the expected increase in turbine sound power levels, by using the measured Meteorological (MET) data, and re-evaluate the noise levels at all the receptor locations;
c) Establish the dominant wind direction from the MET data and its percentage of occurrence. Most of the commercially available propagation models are able to incorporate basic MET data. Using the wind direction data, re-evaluate the noise levels at all salient receptor locations;
d) The results of Steps (a) thru' (c) would aid in setting up statistical analysis of noise levels, its variability and the number of affected residents. Average conclusions about the noise impact and potential mitigation methods if necessary can be established.

vii. Compliance of the wind farm site and potential adverse noise effects, based on acceptable annoyance criterion, can thus be included in the impact analysis to determine the suitability of the wind farm proposal.

The above process is one possible suggestion of the ways in which the current procedures can be revised to incorporate local meteorological conditions at the proposed wind farm sites.

Infrasound from Wind Turbines – Fact, Fiction or Deception

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ABSTRACT

Infrasound is discussed in terms of what it actually is, how the media has dealt with it and what those with limited knowledge say about it. The perception of infrasound occurs at levels higher than the levels produced by wind turbines and there is now agreement amongst acousticians that infrasound from wind turbines is not a problem. Statements on infrasound from objectors are considered and it is shown how these may have caused avoidable distress to residents near wind turbines and also diverted attention from the main noise source, which is the repeating sound of the blades interacting with the tower. This is the noise which requires attention, both to reduce it and to develop optimum assessment methods.

RÉSUMÉ

L'infrason est discuté en termes de ce qu'il est réellement, son traitement dans les médias et par ceux avec des connaissances limitée à son sujet. La perception de l'infrason est qu'il existe à des niveaux plus hauts que ceux produits par des éoliennes, mais il y a maintenant accord parmi les acousticiens que l'infrason des éoliennes n'est pas un problème. Des rapports sur l'infrason par des protestataires sont considérés et on montre comment ceux-ci ont pu causer de la détresse évitable aux résidants près des éoliennes et également divertir l'attention de la source principale de bruit: le son répétitif de l'interaction des lames avec la tour. C'est ce bruit qui exige de l'attention, pour le réduire et pour développer des méthodes optimales d'évaluation.

1. INFRASOUND

A definition of infrasound is: Acoustic oscillations whose frequency is below the low frequency limit of audible sound (about 16Hz). (IEC 1994)

This definition is incorrect, as sound remains audible at frequencies well below 16Hz. For example, measurements of hearing threshold have been made down to 4Hz for exposure in an acoustic chamber (Watanabe and Møller 1990b) and down to 1.5 Hz for earphone listening (Yeowart, Bryan et al. 1967)

The limit of 16Hz, or more commonly considered as 20Hz, arises from the lower frequency limit of the standardized equal loudness hearing contours measured in units of phons, which is a difficult measurement at low frequencies, not from the lower limit of hearing.

2. THE AUDIBILITY OF INFRASOUND

Hearing sensation does not suddenly cease at 20Hz when the frequency is reduced from 21Hz to 19Hz, but continues from 20Hz down to very low frequencies of several Hertz. It is not possible to define an inaudible infrasound range and an audible audio range as separate regions, unless the infrasound range is limited to naturally occurring infrasound of very low frequencies. The range from about 10Hz to 100Hz can be considered as the low frequency region, with possible extensions by an octave at each end of this range, giving 5Hz to 200Hz. There is a very fuzzy boundary between infrasound and low frequency noise, which often causes confusion.

Hearing thresholds in the infrasonic and low frequency region are shown in Fig 1. The solid line above 20Hz is the low frequency end of the ISO standard threshold (ISO:226 2003). The dashed curve, 4Hz to 125Hz, is from Watanabe and Møller (Watanabe and Møller 1990b). There is good correspondence between the two threshold measurements in the overlap region.

The slope of the hearing threshold reduces below about 15Hz from approximately 20dB/octave above 15 Hz to about 12dB/octave below. (Yeowart, Bryan et al. 1967). The common assumption that "infrasound" is inaudible is incorrect, arising from an unfortunate choice of descriptor. "Real" infrasound, at levels and frequencies below audibility are largely natural phenomena, although human activities, such as explosions, also produce infrasound. Microphone arrays for the detection of airborne infrasound are a component of the monitoring for the Nuclear Test Ban Treaty

The median hearing threshold is not a simple delineation between "Can hear - Can't hear", but the threshold is rather variable between individuals, depending on their genetics, prior noise exposure and age (ISO7029 2000). The standard deviation of threshold measurements is typically about 6dB.

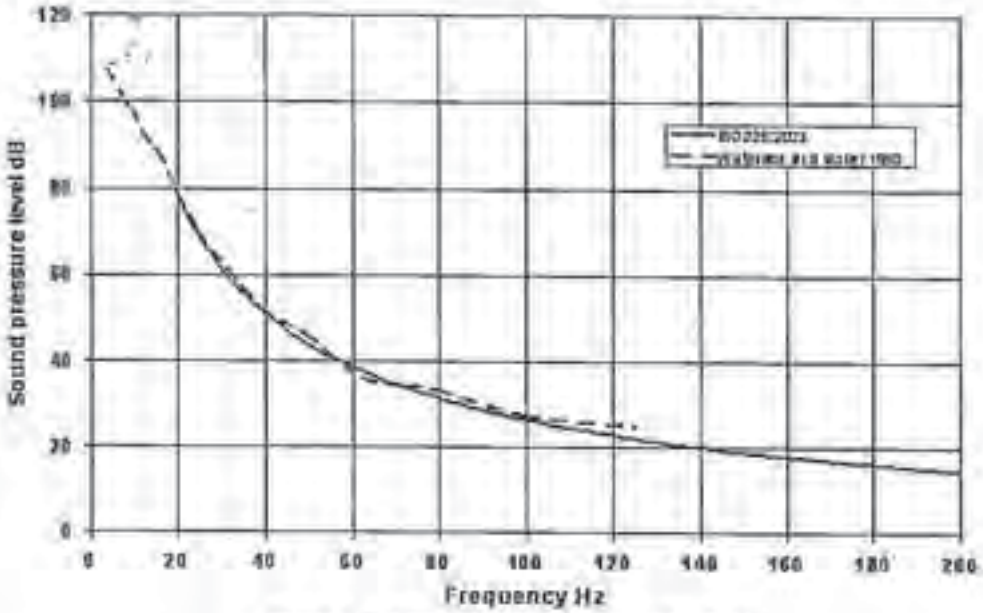

Figure 1. Infrasonic and low frequency threshold

Therefore, it is most unlikely that anyone will be able to hear sound at any frequency which is more than, say, 20dB below its median threshold.

The false concept that infrasound is inaudible, when coupled with the many common misconceptions about its subjective effects, has spawned concerns, particularly expressed in popular publications, which are best described as mythology, rather than fact.

A report reviewing low frequency noise (Leventhall, Benton et al. 2003) is available on the internet.

High levels at very low frequencies: These may result in aural pain, which is not a hearing sensation, but arises from displacements of the middle ear system beyond its comfortable limits. Persons with both hearing ability and hearing loss, and with normal middle ears, exhibit aural pain at a similar stimulus level, which is at about 165dB at 2Hz, reducing to 145dB at 20Hz. Static pressure produces pain at 175 -180dB, whilst eardrum rupture occurs at 185 -190dB (von Gierke and Nixon 1976). A pressure of 5 x 104 Pa, which is about half atmospheric pressure, falls in the 185 -190dB range. A child on a swing experiences infrasound at a level of around 110dB and frequency 0.5Hz, depending on the suspended length and the change in height during the swing.

Natural Infrasound: We are enveloped in naturally occurring infrasound, which is in the range from about 0.01 Hz to 2Hz and is at inaudible levels. The lower limit of one cycle in a hundred seconds separates infrasound, as a propagating wave, from all but the fastest fluctuations in barometric pressure. There are many natural sources of infrasound, including meteors, volcanic eruptions, ocean waves, wind and any effect which leads to slow oscillations of the air. Man made sources include explosions, large combustion processes, slow speed fans and machinery. Much natural infrasound is lower in frequency than 1 Hz and below the hearing threshold. (Bedard and George 2000). Our evolution has been in the presence of natural infrasound.

Alternative receptors: The question arises of whether there is a hierarchy of receptors, of which the ear is the most sensitive except at the lower frequencies, when other receptors may come into prominence. Several vibration and contact detectors reside in the skin, covering different frequency ranges (Johnson 2001). The Pacinian corpuscles are the most sensitive, with a threshold displacement of about 0.002mm in the region of 200Hz,. Their sensitivity into lower frequencies reduces at approximately 50dB per decade from the maximum sensitivity.

The threshold displacement of 0.002mm at 200Hz is similar to the particle displacement in air of a 200Hz sound wave of 94dB (1 Pa) pressure. Since the particle displacement in a sound wave of fixed pressure doubles as the frequency is halved (20dB per decade) inaudible sound waves will not excite these subcutaneous receptors.

There is no reliable evidence that infrasound at levels below its hearing threshold has an adverse effect on the body (Berglund and Lindvall 1995). A recent French study of wind turbine noise confirms that infrasound from wind turbines is not a problem. (Chouard 2006)

Body vibrations: It is known that high levels of low frequency noise excite body vibrations (Leventhall, Benton et al. 2003). The most prominent body response is a chest resonance vibration in the region of 50Hz to 80Hz, occurring at levels above about 80dB, which are audible in this frequency range. The low frequency perception thresholds of normal hearing and profoundly deaf subjects have also been investigated (Yamada, Ikuji et al. 1983), when it was shown that the profoundly deaf subjects perceived noise through their body

only at levels which were in excess of normal thresholds. The threshold of sensation of the deaf subjects was 40-50dB above the hearing threshold of those with normal hearing up to a frequency of 63Hz and greater at higher frequencies. For example about 100dB greater at 1 kHz, at which level perception was by the subjects' residual hearing. Deaf subjects experienced chest vibration in the same frequency range as normal hearing subjects.

The much repeated statement that "infrasound can be felt but not heard" is not supported by these measurements. The erroneous thought processes which led to this confusion are possibly:

Infrasound causes body vibrations - (correct at very high levels)
But infrasound is inaudible - (not correct at very high levels)
Therefore infrasound can be felt but not heard - (not correct)

neglecting that the levels to produce body vibrations are well above the hearing threshold. But, as will be shown later, infrasound is not a problem for modern wind turbines.

The dimensions of noise: Noise is multidimensional. A one dimensional view of noise is the A - weighting, which considers only levels and neglects frequencies. Another one-dimensional view is to consider only frequencies and neglect levels. Developing the dimensions further, two dimensions include both frequency and level (the spectrum), three dimensions adds in the time variations of the noise, whilst higher dimensions include subjective response.

Many lay people take the one dimensional view of infrasound, which is based on frequency alone. They express concern at the presence of any infrasound, irrespective of its level. This is a significant failure of understanding.

Public Perceptions: The Public has been misled by the media about infrasound, resulting in needless fears and anxieties, which possibly arise from confusion of the work on subjective effects, which has been carried out at high, audible levels with the popular mindset that infrasound is inaudible. There have also been misunderstandings fostered in publications and popular science books, considered later.

Early work on low frequency noise and its subjective effects was stimulated by the American space program. Launch vehicles produce high noise levels with maximum energy in the low frequency region. Furthermore, as the vehicle accelerates, the crew compartment is subjected to boundary layer turbulence noise for about two minutes after lift-off. Experiments were carried out in low frequency noise chambers on short term subjective tolerance to bands of noise at very high levels of 140 to 150dB, in the frequency range up to 100Hz (Mohr, Cole et al. 1965). It was concluded that the subjects, who were experienced in noise exposure and who were wearing ear protection, could tolerate both broadband and discrete frequency noise in the range

1 Hz to 100Hz at sound pressure levels up to 150dB. Later work suggests that, for 24 hour exposure, levels of 120-130dB are tolerable below 20Hz. These limits were set to prevent direct physiological damage, not for comfort. (Mohr, Cole et al. 1965; Westin 1975; von Gierke and Nixon 1976).

The American work did not attract media attention, but in the late 1960's two papers from France led to much publicity and speculative exaggerations. (Gavreau, Condat et al. 1966; Gavreau 1968). Although both papers carry "infrasound" in their titles, there is very little on frequencies below 20Hz (Leventhall 2005). Some rather casual and irresponsible experiments of the "try it and see" variety were carried out on exposure of the laboratory staff, primarily using high intensity pneumatic sources at frequencies mainly at the upper end of the low frequency range, or above. For example, 196Hz at 160dB sound level and 340Hz at 155dB sound level. A high intensity whistle at 2600Hz is also included in the "infrasound" papers.

Infrasounds are not difficult to study but they are potentially harmful. For example one of my colleagues, R Levavasseur, who designed a powerful emitter known as the 'Levavasseur whistle' is now a victim of his own inventiveness. One of his larger whistles emitting at 2600Hz had an acoustic power of 1 kW. . ... This proved sufficient to make him a lifelong invalid. (Gavreau 1968)

Of course, 2600Hz is not infrasound, but the misleading implication is that infrasound caused injury to Levavasseur. A point source of sound of power 1 kW will produce a sound level of about 140dB at 1 m, which is a very undesirable exposure at 2600Hz.

Referring to the exposure of 160dB at 196Hz:

...after the test we became aware of a painful 'resonance' within our bodies - everything inside us seemed to vibrate when we spoke or moved. What had happened was that this sound at 160 decibels..... acting directly on the body produced intense friction between internal organs, resulting in sever irritation of the nerve endings. Presumably if the test had lasted longer than five minutes, internal haemorrhage would have occurred. (Gavreau 1968)

96 Hz is not infrasound, but the unpleasant effects at 160dB are described in a paper which is said to be about "Infrasound". Internal haemorrhage is often quoted as an effect of exposure to infrasound. Exposure levels were not given for frequencies of 37Hz and 7Hz, although the 7Hz caused subjective disturbance and vibrations of the laboratory walls. Unfortunately, these papers by Gavreau were seized upon by the press and presented to claim that infrasound was dangerous . For example "The silent killer all around us", London Evening News, 25 May 1974. When work by other investigators detected moderate levels of infrasound in, for example, road vehicles, the press was delighted, leading to "The silent sound menaces drivers" - Daily Mirror, 19 October 1969.

"Danger in unheard ear sounds" The Observer, 21 April 1974.

The most deplorable example, in a book which claimed to have checked its sources, was in "Supernature" by Lyall Watson (Coronet 1973). In this it is claimed that the technician who gave one of Gavreau's high power infrasound sources its trial run "fell down dead on the spot" and that two infrasonic generators "focused on a point even five miles away produce a resonance that can knock a building down as effectively as a major earthquake".

These fictitious statements are, of course, totally incorrect but are clear contributors to some of the unfounded concerns which the public feels about infrasound. One can detect a transition from Gavreau and his colleague feeling ill after exposure to the high level of 196Hz to "fell down dead on the spot" and a further transition from laboratory walls vibrating to "can knock a building down", transitions which resulted from repeated media exaggerations over a period of five or six years.

The misunderstanding between infrasound and low frequency noise continues to the present day. A newspaper article on low frequency noise from wind turbines (Miller 24 January 2004) , opens with:

Onshore wind farms are a health hazard to people living near them because of the low-frequency noise that they emit, according to new medical studies. A French translation of this article for use by objectors' groups opens with:

De nouvelles etudes medicales indiquent que les eoliennes terrestres representent un risque pour la sante des gens habitant a proximite, a cause d'emission d'infrasons.

The translation of low frequency noise into infrasons continues through the article. This is not a trivial misrepresentation because, following on from Gavreau, infrasound has been connected with many misfortunes, being blamed for problems for which some other explanation had not yet been found e.g., brain tumours, cot deaths of babies, road accidents.

Infrasound, and its companion low frequency noise, now occupy a special position in the national psyche of a number of countries, where they lie in wait for an activating trigger to re-generate concerns of effects on health. Earlier triggers have been defence establishments and gas pipelines. A current trigger is wind turbines.

3 INFRASOUND AND LOW FREQUENCY NOISE FROM WIND TURBINES

Early designs of downwind turbines produced pressure pulses at about once per second, which were high enough to cause vibrations in lightweight buildings nearby. (Shepherd and Hubbard 1991). A series of pulses occurring at one per second analyses into a harmonic series in the infrasound region, which is the origin of the link between wind turbines and infrasound. One could discuss whether the Fourier time-frequency duality is misleading on this point, since it was the effects of peaks of the pulses which caused the building vibration, not a continuous infrasonic wave. Similar vibration would have occurred with a faster stream of pulses, with the limiting condition that the pulse repetition rate was lower than the period of the vibration.

Modern up-wind turbines produce pulses which also analyse as infrasound, but at low levels, typically 50 to 70dB, well below the hearing threshold. Infrasound can be neglected in the assessment of the noise of modern wind turbines (Jakobsen 2004)

Fig 2 shows the infrasonic and low frequency noise at 65m from a 1.5MW wind turbine on a windy day. The fol-

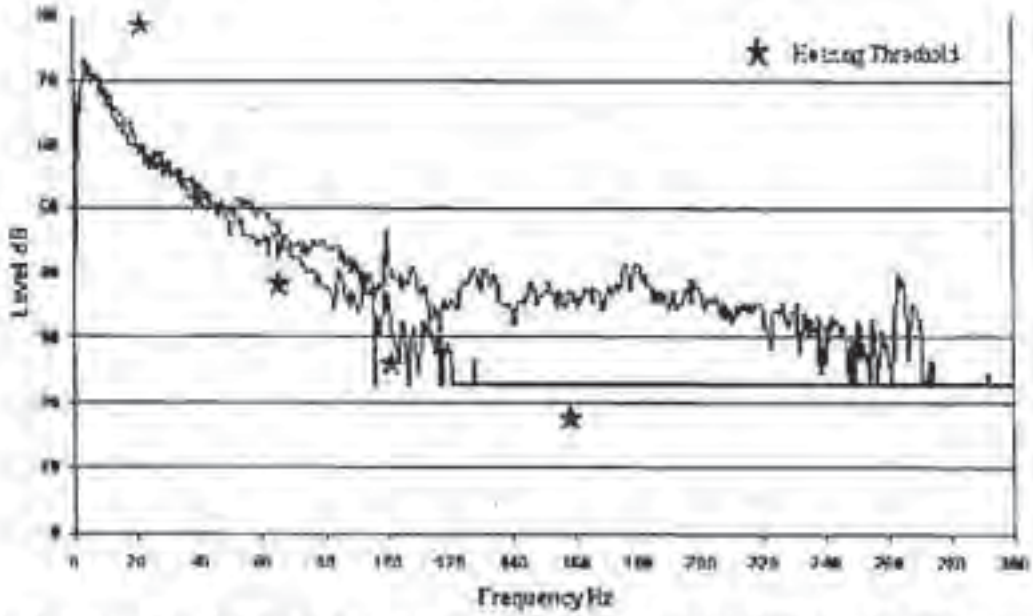

Figure 2. *Spectrum of a modern upwind wind turbine - Upper trace Wind Turbine Noise. Lower trace Background noise.*

lowing should be noted.

- The fall off below about 5Hz is an instrument effect. The background noise actually increases down to the frequencies of atmospheric pressure variations.
- Frequencies below 40Hz cannot be distinguished from background noise due to wind.
- The wind turbine noise and background noise separate above about 40Hz and both rise above the median hearing threshold.
- The measurements were taken at 65m. Levels are likely to be about 15dB lower at normal separation distances

On the occasions, such as unusually turbulent inflow conditions, when low frequency noise is produced by wind turbines, it may not be perceived as a noise, but rather as an unidentified adverse component in the environment, which disappears if the turbines stop, or if the inflow conditions change. This is because we are not accustomed to listening to low levels of broad band low frequency noise and, initially, do not always recognise it as a "noise", but more as a "disturbance" in the environment. An analogy is with air-conditioning rumble noise, which is noticed when it stops.

What Objectors Say Objectors have eagerly grasped the media hype on infrasound and low frequency noise and used it to engender concerns about wind turbine developments. In this they have, possibly, done a disservice to the communities they were established to help, through raising false concerns and diverting attention from more important aspects of the development. Two examples are as follows.

In the UK there is an Advertising Standards Authority(ASA), to which deceptive adverts can be referred for assessment. An objectors' group (Ochils Environmental Protection Group) issued a leaflet "FACTS ABOUT WIND POWER", containing a number of assertions including:

"... wind turbines still create noise pollution, notably 'infra sound' - inaudible frequencies which nevertheless cause stress-related illness ..."

In their Judgment (April 02, 2004), the ASA concluded that the objectors had not produced evidence to substantiate their claim.

In the USA, a high profile objector (Nina Pierpont of Malone NY) placed an advertisement in a local paper, consisting entirely of selected quotations from a previously published technical paper by van den Berg (Van den Berg 2004). However the comment "[i.e. infrasonic]", as shown in Fig 3, was added in the first line of the first quotation in a manner which might mislead naive readers into believing that it was part of the original.

The van den Berg paper was based on A-weighted measurements and had no connection with infrasound. So, not only is the advertisement displaying the advertiser's self deception, but this has also been propagated to others who have read it. To mistakenly connect the noise to infrasound, which has unpleasant associations is, however, a way to gather support. (When a person has adopted a particular mindset, new information is processed to support that mindset. We all do this.)

It takes little technical knowledge to be aware that a modulated high frequency wave does not contain the modulation components. For example, an amplitude modulated radio wave contains the carrier wave and sidebands, which are close in frequency to the carrier. The fluctuations of wind turbine noise (swish – swish) are a very low frequency modulation of the aerodynamic noise, which is typically in the region of 500 - 1000Hz. The modulation occurs from a change in radiation characteristics as the blade passes the tower, but the modulating frequencies do not have an independent and separate existence.

The comment, [i.e. infrasonic], added into Fig 3 gives incorrect information. Claims of infrasound are irrelevant and possibly harmful, should they lead to unnecessary fears.

PAID ADVERTISEMENT

Wind Turbines & Infrasound: What the latest research says

"At night the wind turbines cause a low pitched thumping [i.e., infrasonic] sound superimposed on a broadband 'noisy' sound, the 'thumps' occurring at the rate at which blades pass a turbine tower.... The number and severity of noise complaints near the wind park are at least in part explained by the two main findings of this study: actual sound levels are considerably higher than predicted, and wind turbines can produce sound with an impulsive character."

-- Professor Frits G.P. van den Berg, University of Groningen, the Netherlands, November 2004 (see excerpts from research articles, below)

Figure 3 Part of an advertisement placed by an objector in the Malone (NY) Telegram, 25th February 2005.

It has been shown that fear of a noise source, for example that aircraft might crash, increases the extra annoyance of a person with a high fear of a crash by up to 19dB DNL equivalent, compared with a person who has no fear (Miedema and Vos 1999).

Fear of a source is not the same as fear of the noise itself, but it is understandable that those who fear the effects of a noise upon their health will be less tolerant of the noise than those who do not fear it. We can only speculate upon the harm which objectors might have done by, for example, taking a one dimensional view of infrasound and publicising the subjective effects of high levels of both infrasound and low frequency noise in a manner which implies that the effects may also be caused by the low levels produced by wind turbines.

4 WIND TURBINE NOISE

It has been shown above that there is insignificant infrasound from wind turbines and that there is normally little low frequency noise. Turbulent air inflow conditions cause enhanced levels of low frequency noise, which may be disturbing, but the overriding noise from wind turbines is the fluctuating audible swish, mistakenly referred to as "infrasound" or "low frequency noise". Objectors uninformed and mistaken use of these terms (as in Fig 3), which have acquired a number of anxiety-producing connotations, has led to unnecessary fears and to unnecessary costs, such as for re-measuring what was already known, in order to assuage complaints.

Attention should be focused on the audio frequency fluctuating swish, which some people may well find to be very disturbing and stressful, depending on its level. The usual equivalent level measurements and analyses are incomplete, as these measurements are taken over a time period which is much longer than the fluctuation period and information on the fluctuations is lost. A time varying sound is more annoying than a steady sound of the same average level and this is accounted for by reducing the permitted level of wind turbine noise. However, more work is required to ensure that the optimum levels have been set.

5 CONCLUSIONS

- Infrasound from wind turbines is below the audible threshold and of no consequence.
- Low frequency noise is normally not a problem, except under conditions of unusually turbulent inflow air.
- The problem noise from wind turbines is the fluctuating swish. This may be mistakenly referred to as infrasound by those with a limited knowledge of acoustics, but it is entirely in the normal audio range and is typically 500Hz to 1000Hz. It is difficult to have a useful discourse with objectors whilst they continue to use acoustical terms incorrectly. This is unfortunate, as there are wind turbine installations which may have noise problems.
- It is the swish noise on which attention should be focused, in order to reduce it and to obtain a proper estimate of its effects. It will then be the responsibility of legislators to fix the criterion levels. However, although the needs of sensitive persons may influence decisions, limits are not normally set to satisfy the most sensitive.

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The Impact of Wind Power Projects on Residential Property Values in the United States: A Multi-Site Hedonic Analysis

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Environmental Energy Technologies Division

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The Impact of Wind Power Projects on Residential Property Values in the United States: A Multi-Site Hedonic Analysis

Abstract

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Executive Summary

Overview

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n = 7,459) from ten communities surrounding 24 existing wind power facilities spread across multiple parts of the U.S. (e.g., nine states). Homes included in this sample are located from 800 ft to over five miles from the nearest wind energy facility, and were sold at any point from before wind facility announcement to over four years after the construction of the nearby wind project. Each of the homes that sold was visited to determine the degree to which the wind facility was likely to have been visible at the time of sale and to collect other essential data.

To assess the potential impacts of all three of the property value stigmas described earlier, a base hedonic model is applied as well as seven alternative hedonic models each designed to investigate the reliability of the results and to explore other aspects of the data (see Table ES - 1 below). In addition, a repeat sales model is analyzed, and an investigation of possible impacts on sales volumes is

What Is a Hedonic Pricing Model?

Hedonic pricing models are frequently used by economists and real estate professionals to assess the impacts of house and community characteristics on property values by investigating the sales prices of homes. A house can be thought of as a bundle of characteristics (e.g., number of square feet, number of bathrooms). When a price is agreed upon by a buyer and seller there is an implicit understanding that those characteristics have value. When data from a large number of residential transactions are available, the individual marginal contribution to the sales price of each characteristic for an average home can be estimated with a hedonic regression model. Such a model can statistically estimate, for example, how much an additional bathroom adds to the sale price of an average home. A particularly useful application of the hedonic model is to value non-market goods – goods that do not have transparent and observable market prices. For this reason, the hedonic model is often used to derive value estimates of amenities such as wetlands or lake views, and disamenities such as proximity to and/or views of high-voltage transmission lines, roads, cell phone towers, and landfills. It should be emphasized that the hedonic model is not typically designed to appraise properties (i.e., to establish an estimate of the market value of a home at a specified point in time), as would be done with an automated valuation model. Instead, the typical goal of a hedonic model is to estimate the marginal contribution of individual house or community characteristics to sales prices.

[2] Many of these studies are summarized in the following reviews: Kroll and Priestley (1992); McCann (1999); Bateman et al. (2001); Boyle and Kiel (2001); Jackson (2001); Simons and Saginor (2006); and Leonard et al. (2008). For further discussion of the hedonic model and its application to the quantification of environmental stigmas see Jackson (2005) and Simons (2006a).

conducted. Though some limitations to the analysis approach and available data are acknowledged, the resulting product is the most comprehensive and data-rich analysis to date in the U.S. or abroad on the impacts of wind projects on nearby property values.

Analysis Findings

Table ES - 1 describes the ten resulting statistical models that are employed to investigate the effects of wind facilities on residential sales prices, and the specific stigmas that those models investigate. Though all models test some combination of the three possible stigmas, they do so in different ways. For instance, the Base Model asks the question, All else being equal, do homes near wind facilities sell for prices different than for homes located farther away , while the All Sales Model asks, All else being equal, do homes near wind facilities that sell after the construction of the wind facility sell for prices different from similar homes that sold before the announcement and construction of the facility Each model is therefore designed to not only test for the reliability of the overall results, but also to explore the myriad of potential effects from a variety of perspectives. Table ES-2 summarizes the results from these models.

Table ES - 1: Description of Statistical Models

Statistical Model	Description
Base Hedonic Model	Using only post-construction transactions (those that occurred after the wind facility was built), this model investigates all three stigmas in a straightforward manner
Alternative Hedonic Models	
iew Stability	Using only post-construction transactions, this model investigates whether the Scenic ista Stigma results from the Base Model are independent of the uisance and Area Stigma results
istance Stability	Using only post-construction transactions, this model investigates whether the uisance and Area Stigma results from the Base Model are independent of the Scenic ista Stigma results
Continuous istance	Using only post-construction transactions, this model investigates Area and uisance Stigmas by applying a continuous distance parameter as opposed to the categorical variables for distance used in the previous models
All Sales	Using all transactions, this model investigates whether the results for the three stigmas change if transactions that occurred before the announcement and construction of the wind facility are included in the sample
Temporal Aspects	Using all transactions, this model further investigates Area and uisance Stigmas and how they change for homes that sold more than two years pre-announcement through the period more than four years post-construction
rientation	Using only post-construction transactions, this model investigates the degree to which a home s orientation to the view of wind turbines affects sales prices
verlap	Using only post-construction transactions, this model investigates the degree to which the overlap between the view of a wind facility and a home s primary scenic vista affects sales prices
Repeat Sales Model	Using paired transactions of homes that sold once pre-announcement and again post-construction, this model investigates the three stigmas, using as a reference transactions of homes located outside of five miles of the nearest wind turbine and that have no view of the turbines
Sales Volume Model	Using both pre-announcement and post-construction transactions, this model investigates whether the rate of home sales (not the price of those sales) is affected by the presence of nearby wind facilities

Table ES-2: Impact of Wind Projects on Property Values: Summary of Key Results

Statistical Model	Is there statistical evidence of: Area Stigma?	Scenic Vista Stigma?	Nuisance Stigma?	Section Reference
Base Model	o	o	o	*Section 4*
iew Stability	ot tested	o	ot tested	*Section 5.1*
istance Stability	o	ot tested	o	*Section 5.1*
Continuous istance	o	o	o	*Section 5.2*
All Sales	o	o	Limited	*Section 5.3*
Temporal Aspects	o	o	o	*Section 5.4*
rientation	o	o	o	*Section 5.5*
verlap	o	Limited	o	*Section 5.6*
epeat Sales	o	Limited	o	*Section 6*
Sales olume	o	ot tested	o	*Section 7*

"No"…….. No statistical evidence of a negative impact
"Yes"…….. Strong statistical evidence of a negative impact
"Limited"…….. Limited and inconsistent statistical evidence of a negative impact
"Not tested"…… This model did not test for this stigma

Base Model Results

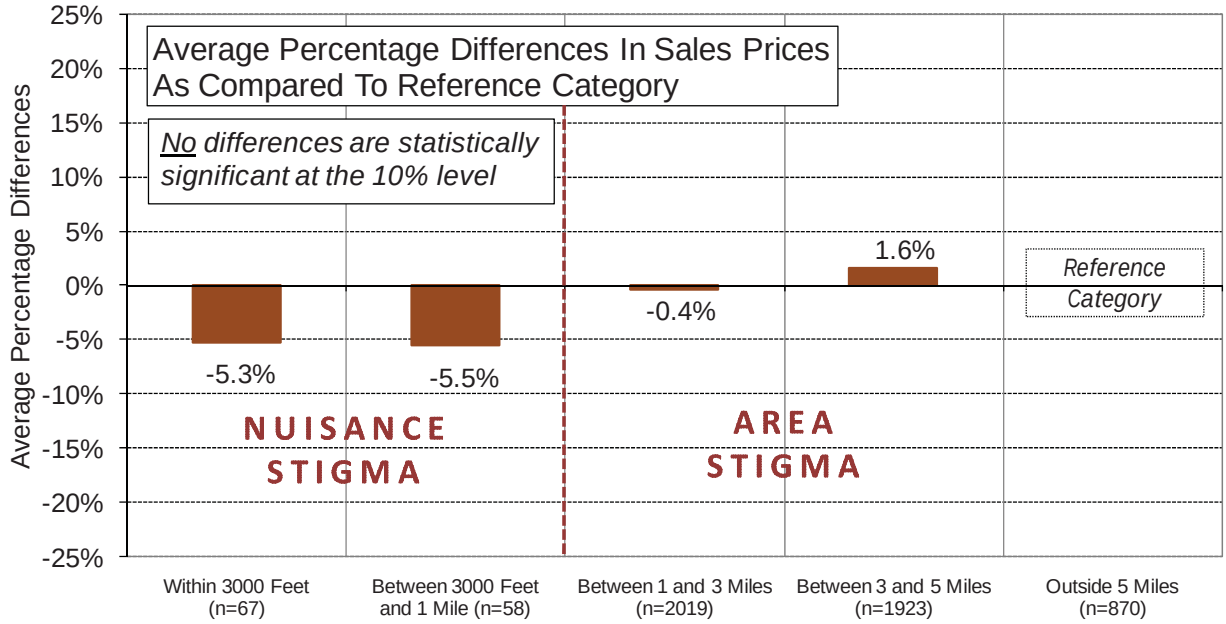
The Base Model serves as the primary model and allows all three stigmas to be explored. In sum, this model finds no persuasive evidence of any of the three potential stigmas: neither the view of the wind facilities nor the distance of the home to those facilities is found to have any consistent, measurable, and statistically significant effect on home sales prices.

- Area Stigma: To investigate Area Stigma, the model tests whether the sales prices of homes situated anywhere outside of one mile and inside of five miles of the nearest wind facility are measurably different from the sales price of those homes located outside of five miles. o statistically significant differences in sales prices between these homes are found (see Figure ES-1).
- Scenic ista Stigma: For Scenic ista Stigma, the model is first used to investigate whether the sales prices of homes with varying scenic vistas - absent the presence of the wind facility - are measurably different. The model results show dramatic and statistically significant differences in this instance (see Figure ES-2); not surprisingly, home buyers and sellers consider the scenic vista of a home when establishing the appropriate sales price. onetheless, when the model tests for whether homes with minor, moderate, substantial, or extreme views of wind turbines have measurably different sales prices, no statistically significant differences are apparent (see Figure ES-).
- uisance Stigma: Finally, for uisance Stigma, the model is used to test whether the sales prices of homes situated inside of one mile of the nearest wind energy facility are measurably different from those homes located outside of five miles. Although sample size is somewhat limited in this case, the model again finds no persuasive statistical evidence that wind

125 homes were located inside of one mile of the nearest wind facility and sold post-construction.

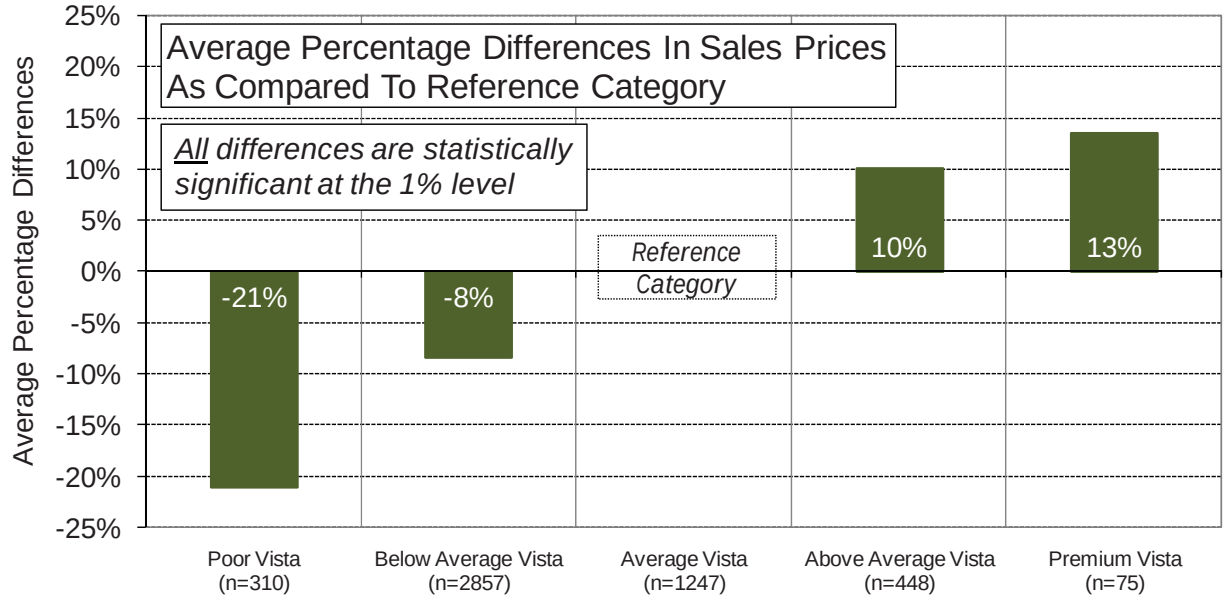
facilities measurably and broadly impact residential sales prices (see Figure ES-1 and later results).

Figure ES-1: Base Model Results: Area and Nuisance Stigma



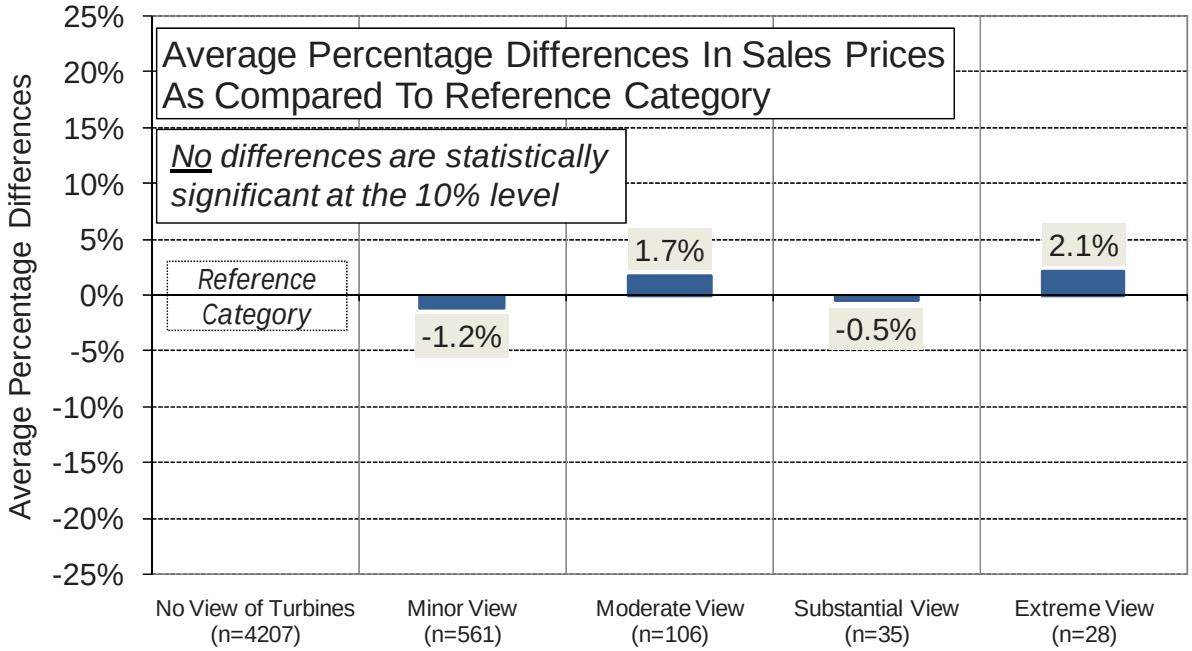
The reference category consists of transactions for homes situated more than five miles from the nearest turbine, and that occured after construction began on the wind facility

Figure ES-2: Base Model Results: Scenic Vista



The reference category consists of transactions for homes with an Average Vista, and that occured after construction began on the wind facility

Figure ES-3: Base Model Results: Scenic Vista Stigma



The reference category consists of transactions for homes without a view of the turbines, and that occured after construction began on the wind facility

The seven alternative hedonic models and the additional analysis contained in the epeat Sales and Sales olume Models (see Table ES-2) provide a fuller picture of the three stigmas and the robustness of the Base Model results.

Area Stigma: Other Model Results

Concentrating first on Area Stigma, the results from all of the models are similar: there is no statistical evidence of a widespread Area Stigma among the homes in this sample. Homes in the study areas analyzed here do not appear to be measurably stigmatized by the arrival of a wind facility, regardless of when those homes sold in the wind project development process and regardless of whether the homes are located one mile or five miles away from the nearest facility.

In the All Sales Model, for example, after adjusting for inflation,[4] homes that sold after wind facility construction and that had no view of the turbines are found to have transacted for higher prices - not lower - than those homes that sold prior to wind facility construction. Moreover, in the Temporal Aspects Model, homes that sold more than two years prior to the announcement of the wind facility and that were located more than five miles from where the turbines were eventually located are found to have transacted for lower prices - not higher - than homes situated closer to the turbines and that sold at any time after the announcement and construction of the wind facility (see Figure ES - 4). Further, in the epeat Sales Model, homes located near the wind facilities that transacted more than once were found to have appreciated between those sales by an amount that was no different from that experienced by homes located in an area

[4] All sales prices in all models are adjusted for inflation, but because this model (and the Temporal Aspects Model) deals with time explicitly, it is mentioned specifically here.

many miles away from the wind facilities. Finally, as shown in Table ES-2, none of the other models identified evidence of a broadly negative and statistically significant Area Stigma.

Scenic Vista Stigma: Other Model Results

With respect to Scenic ista Stigma, the seven alternative hedonic models and the additional analysis contained in the epeat Sales Model find little consistent evidence of a broadly negative and statistically significant impact. Although there are 7 0 residential transactions in the sample that involve homes that had views of a wind facility at the time of sale, 160 of which had relatively significant views (i.e., a rating higher than Minor), none of the various models finds strong statistical evidence that the view of a nearby wind facility impacts sales prices in a significant and consistent manner.

When concentrating only on the view of the wind facilities from a home (and not testing for Area and uisance Stigmas simultaneously), for example, the results from the iew Stability Model are very similar to those derived from the Base Model, with no evidence of a Scenic ista Stigma. Similarly, the All Sales Model finds that homes that sold after wind facility construction and that had a view of the facility transacted for prices that are statistically indistinguishable from those homes that sold at any time prior to wind facility construction. The rientation Model, meanwhile, fails to detect any difference between the sales prices of homes that had either a front, back, or side orientation to the view of the wind facility. As shown in Table ES-2, the Continuous istance and Temporal Aspects models also do not uncover any evidence of a broadly negative and statistically significant Scenic ista Stigma.

In the epeat Sales Model, some limited evidence is found that a Scenic ista Stigma may exist, but those effects are weak, fairly small, somewhat counter-intuitive, and are at odds with the results of other models. This finding is likely driven by the small number of sales pairs that are located within one mile of the wind turbines and that experience a dramatic view of those turbines. Finally, in the verlap Model, where the degree to which a view of the wind facility overlaps the primary scenic vista from the home is accounted for, no statistically significant differences in sales prices are detected between homes with somewhat or strongly overlapping views when compared to those homes with wind turbine views that did not overlap the primary scenic vista. Though this model produces some weak evidence of a Scenic ista Stigma among homes with Minor views of wind facilities, the same model finds that the sales prices of those homes with views that barely overlap the primary scenic vista are positively impacted by the presence of the wind facility. When these two results are combined, the overall impact is negligible, again demonstrating no persuasive evidence of a Scenic ista Stigma.

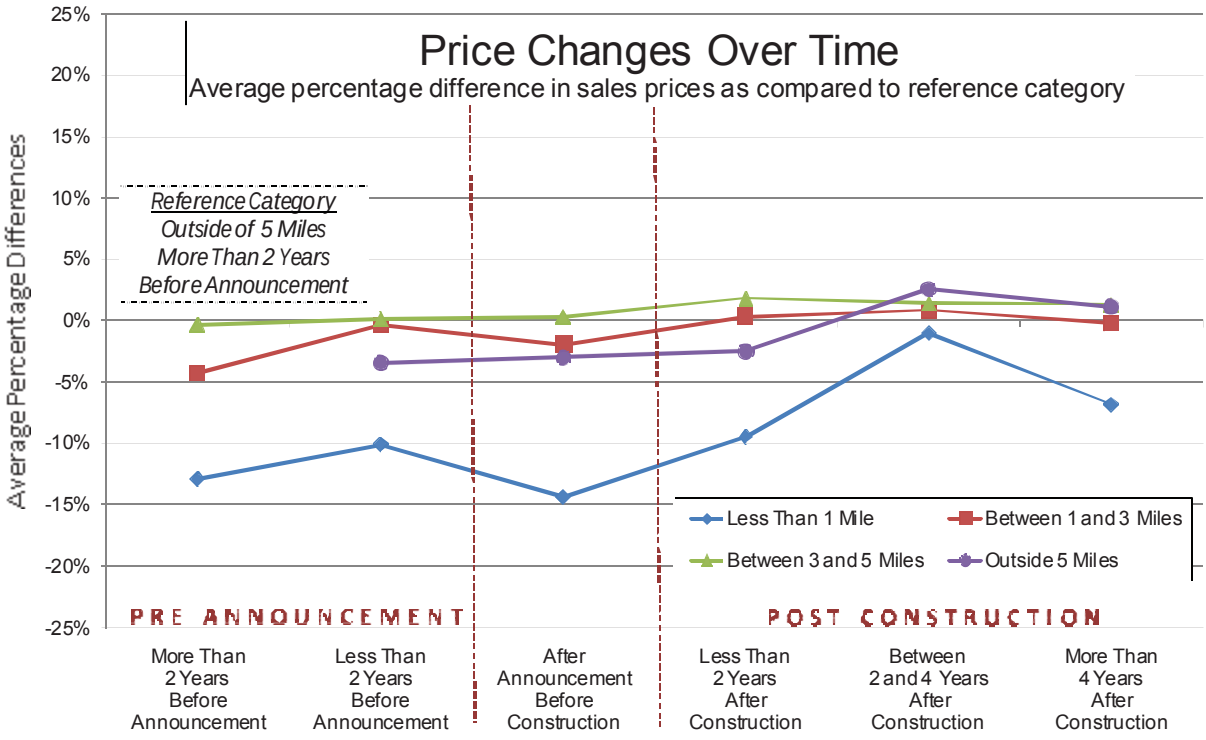
Nuisance Stigma: Other Model Results

esults for uisance Stigma from the seven alternative hedonic models and the additional analysis contained in the epeat Sales and Sales olume Models support the Base Model results. Taken together, these models present a consistent set of results: homes in this sample that are within a mile of the nearest wind facility, where various nuisance effects have been posited, have not been broadly and measurably affected by the presence of those wind facilities. These results imply that uisance Stigma effects are either not present in this sample, or are too small and/or infrequent to be statistically distinguished.

In the Distance Stability Model, for example, when concentrating only on the distance from homes to the nearest wind turbine (and not testing for Scenic Vista Stigma simultaneously), the results are very similar to those derived from the Base Model, with no statistical evidence of a Nuisance Stigma. These results are corroborated by the Continuous Distance, Orientation, Overlap, and Repeat Sales Models, none of which find a statistically significant relationship between distance and either sales prices or appreciation rates. Relatedly, the Sales Volume analysis finds no evidence that homes located within one mile of the nearest wind turbine are sold any more or less frequently than homes located farther away from the wind facilities.

In the All Sales Model, a weakly significant difference is found between the sales prices of homes located between 1000 feet and one mile of the nearest wind facility and the homes that sold before the announcement of the wind facility. This effect, however, is largely explained by the results of the Temporal Aspects Model, shown in Figure ES - 4. The Temporal Aspects Model finds that homes located within one mile of where the wind turbines would eventually be located sold for depressed prices well before the wind facility was even announced or constructed. In all time periods following the commencement of wind facility construction, however, inflation-adjusted sales prices increased - not decreased - relative to pre-announcement levels, demonstrating no statistical evidence of a Nuisance Stigma. The results from the All Sales Model (and, for that matter, the negative, albeit statistically insignificant coefficients inside of one mile in the Base Model, see Figure ES-1) are therefore an indication of sales price levels that preceded wind facility announcement construction, and that are not sustained after construction.

Figure ES - 4: Temporal Aspects Model Results: Area and Nuisance Stigma



The reference category consists of transactions of homes situated more than five miles from where the nearest turbine would eventually be located and that occurred more than two years before announcement of the facility

Conclusions and Further Research Needs

Though each of the analysis techniques used in this report has strengths and weaknesses, the results as a whole are strongly consistent in that none of the models uncovers conclusive evidence of the presence of any of the three property value stigmas that might be present in communities surrounding wind power facilities. Therefore, based on the data sample and analysis presented here, no evidence is found that home prices surrounding wind facilities are consistently, measurably, and significantly affected by either the view of wind facilities or the distance of the home to those facilities. Although the analysis cannot dismiss the possibility that individual homes or small numbers of homes have been or could be negatively impacted, it finds that if these impacts do exist, they are either too small and/or too infrequent to result in any widespread, statistically observable impact. Moreover, to the degree that homes and wind facilities in this sample are similar to homes and facilities in other areas of the United States, the results presented here are expected to be transferable to other areas.

This work builds on the existing literature in a number of respects, but there remain a number of areas for further research. The primary goal of subsequent research should be to concentrate on those homes located closest to wind facilities, where the data sample herein was the most limited. Additional research of the nature reported in this paper could be pursued, but with a greater number of transactions, especially for homes particularly close to wind facilities. A more detailed analysis of sales volume impacts may also be fruitful, as would an assessment of the potential impact of wind facilities on the length of time homes are on the market in advance of an eventual sale. Finally, it would be useful to conduct a survey of those homeowners living close to existing wind facilities, and especially those residents who have bought and sold homes in proximity to wind facilities after facility construction, to assess their opinions on the impacts of wind project development on their home purchase and sales decisions.

1. Introduction

Wind power development has expanded dramatically in recent years (WEC, 2009). Although the percent of electricity supplied to the U.S. and globally from wind power projects installed through 2008 remains relatively low (1.9 and 1.5 , respectively) (Wiser and Bolinger, 2009), there are expectations that those percentages will rise and that wind energy could contribute a significant percentage of future electricity supply (WEC, 2008; Wiser and Hand, 2010). Most recently, President bama, in his 2009 State of the Union address, called for a doubling of renewable energy in three years (by 2012), and in 2008 the U.S. epartment of Energy produced a report that analyzed the feasibility of meeting 20 of U.S. electricity demand with wind energy by 20 0 (US E, 2008).

To meet these goals, a significant amount of wind project development activity would be required. The average size of wind power projects built in the U.S. in 2007 and 2008 was approximately 100 MW (Wiser and Bolinger, 2009) and the total amount of capacity required to reach 20 wind electricity is roughly 00,000 MW (US E, 2008). Therefore, to achieve 20 wind electricity by 20 0, a total of ,000 wind facilities may need to be sited and permitted. Most permitting processes in the U.S. require some form of environmental impact assessment, and some form of public involvement in the siting process. Though surveys show that public acceptance is high in general for wind energy (e.g., Wolsink, 2000; Firestone and Kempton, 2006), a variety of concerns are often expressed on the local level that can impact the length and outcome of the siting and permitting process. These concerns range from the potential impacts of wind projects on wildlife habitat and mortality, radar and communications systems, ground transportation and historic and cultural resources, to aesthetic and property value concerns as well as potential nuisance and health impacts. As a result, a variety of siting and permitting guidelines (AWEA, 2008) and impact assessments (AS, 2007) have been completed.

Surveys of local communities considering wind facilities have consistently ranked adverse impacts on aesthetics and property values in the top tier of concerns (e.g., BBC C, 2005; Firestone and Kempton, 2006). evelopers of wind energy echo this assessment: they ranked aesthetics and property values as two of the top concerns (first and third respectively) for individuals or communities opposed to wind power development (Paul, 2006). Local residents have even brought suit against a developer over property values (ale ankin v. FPL, 2008), and some developers have responded to these concerns by offering neighbor agreements that compensate nearby homeowners for the potential impacts of wind projects.

The two concerns of aesthetics and property values are intrinsically linked. It is well established that a home s value will be increased if a high-quality scenic vista is enjoyed from the property (e.g., Seiler et al., 2001). Alternatively, it is reasonable to assume that if a home s scenic vista overlaps with a view of a disamenity, the home might be devalued, as has been found for high-voltage transmission lines (H TL) (Kroll and Priestley, 1992; es- osiers, 2002). Whether a view of wind turbines similarly impacts home values is a key topic of debate in local siting decisions. Aesthetics alone, however, is not the only pathway through which wind projects might impact residential property values. istance to the nearest wind turbine, for example, might also have an impact if various nuisance effects are prominent, such as turbine noise,

shadow flicker,[5] health or safety concerns, or other impacts, real or perceived. In this way, property values near wind turbines might be impacted in the same way as homes near roads might be devalued (Bateman et al., 2001). Additionally, there is evidence that proximity to a disamenity, even if that disamenity is not visible and is not so close as to have obvious nuisance effects, may still decrease a home s sales price, as has been found to be the case for landfills (Thayer et al., 1992).

Taken together, these general concerns about the possible impacts of wind projects on residential property values can be loosely categorized into three potential stigmas:

- Area Stigma: A concern that the general area surrounding a wind energy facility will appear more developed, which may adversely affect home values in the local community regardless of whether any individual home has a view of the wind turbines.
- Scenic ista Stigma: A concern that a home may be devalued because of the view of a wind energy facility, and the potential impact of that view on an otherwise scenic vista.
- uisance Stigma: A concern that factors that may occur in close proximity to wind turbines, such as sound and shadow flicker, will have a unique adverse influence on home values.

These three potential stigmas are not mutually exclusive and could, in theory, be present in part or in combination for any single home. Consequently, all three potential impacts must be considered when analyzing the effects of wind facilities on residential sales prices.

Although concerns about the potential impact of wind projects on residential property values are often mentioned in siting cases, the state of the existing literature on this topic leaves much to be desired. To some extent, the growing body of research investigating this topic has come to opposing conclusions. The most recent and comprehensive of these studies have often concluded that no widespread impacts of wind projects on residential property values are apparent (Hoen, 2006; Sims and ent, 2007; Sims et al., 2008). At the same time, pre-construction surveys of both homeowners and real estate experts have sometimes found an expectation of negative impacts (e.g. Haughton et al., 2004), and post-construction appraisals have sometimes come to similar conclusions (McCann, 2008; Kielisch, 2009). iven the state of the literature, it is not uncommon for local siting and permitting processes to involve contradicting testimony from experts, as occurred in 2004 when the Public Service Commission of Wisconsin heard opposing conclusions from two studies conducted by experienced home valuation experts (Poletti, 2005; arem, 2005).

This report contains the most comprehensive and data-rich analysis to date on the potential impacts of wind projects on nearby residential sales prices. ata from 7,459 residential transactions were collected from the surrounding communities of 24 individual wind projects in nine states and 14 counties in the United States.[6] Because of the large sample size, the diversity of wind projects included in the analysis, and the depth of information collected, a number of different analyses were possible. Specifically, this report relies heavily on a hedonic regression

[5] Shadow flicker occurs when the sun shines through the wind turbine blades when at a low angle to the horizon and shadows are cast on a window or interior wall of a residence (AS, 2007).

[6] The majority of the analysis only includes homes that sold after wind facility construction began, totaling 4,9 7 transactions.

model[7] and uses various forms of that model to investigate potential effects and to confirm the robustness of the resulting findings. To further investigate the robustness of the results, a repeat sales model[8] and a sales volume model[9] are also utilized. In sum, this work builds and improves on the previous literature, and provides an in-depth assessment of the question of whether residential property values in the United States have been affected, in a statistically measurable way, by views of and proximity to wind power facilities.

The remainder of this report is structured as follows. The next section discusses the hedonic model in general, its application to environmental disamenities research, and some potentially analogous results drawn from these studies. This is followed by a summary of the existing literature that has investigated the effects of wind energy on residential property values. The report then turns to the data used in the analysis, a discussion of the primary (or base) hedonic model, and an analysis of the results from that statistical model. Following that, a set of alternative hedonic models are estimated, as well as a repeat sales model and sales volume model, to test for the robustness of the base model results and to explore other aspects of the data. Taking into account the full set of results presented earlier, the report then discusses the three stigmas that may lead to wind projects impacting residential property values, and summarizes how the analysis informs the existence and magnitude of these potential effects. The report ends with a brief conclusion, and a discussion of future research possibilities. A number of appendices follow the conclusion, and contain detailed information on each wind project study area, the data collection instrument and qualitative rating systems used in the field research, the investigation of the best base model, the hedonic model assumptions and related tests, and full results from all of the additional statistical models estimated in the report.

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[7] The hedonic regression model, which was briefly described in a sidebar in the Executive Summary, is described in detail in Section 2.1.

[8] A repeat sales model uses, as its dataset, only those homes that have sold more than once. By comparing annual appreciation rates of homes that sold once before facility announcement, and again after construction, it can be tested, in an alternative fashion, if home values are affected by the distance to or view of nearby wind turbines.

[9] Sales volume can be defined as the percentage of homes that fit a certain criteria (e.g. single family, on less than 25 acres, zoned residential, assessed for more than 10,000) that actually did sell. By comparing sales volumes at various distances to wind facilities, before and after the facility was built, a further robustness test is possible.

2. Previous Research

Hedonic pricing models are frequently used to assess the marginal impacts of house and community characteristics on sales prices and by extension on property values in general. Because the hedonic model is the primary statistical method used in this report, this section begins by describing the model in more detail and providing some relevant examples of its use. The section then reviews the existing literature on the effects of wind energy facilities on surrounding property values, highlights the shortcomings of that literature, and outlines how the present research addresses those shortcomings.

2.1. Hedonic Models and Environmental Disamenities

A house can be thought of as a bundle of characteristics (e.g., number of square feet, number of bathrooms, number of fireplaces, and amount of acreage). When a price is agreed upon between a buyer and seller there is an implicit understanding that those characteristics have value. When data from a number of sales transactions are available, the individual marginal contribution to the sales price of each characteristic can be estimated with a hedonic regression model (osen, 1974; Freeman, 1979). This relationship takes the basic form:

Sales price = *f* (house structural characteristics, other factors)

where house structural characteristics might include, but are not limited to, the number of square feet of living area, bathrooms, and fireplaces, the presence of central AC and the condition of the home, and other factors might include, but are not limited to, home site characteristics (e.g., number of acres), neighborhood characteristics (e.g., school district), market conditions at the time of sale (e.g., prevailing mortgage interest rates), and surrounding environmental conditions (e.g., proximity to a disamenity or amenity).

The relationship between the sales price of homes and the house characteristics and other factors can take various forms. The most common functional form is the semi-log construction where the dependent variable is the natural log of the inflation adjusted sales price, and the independent variables are unadjusted (not transformed) home characteristics and other factors. The usefulness of this form of hedonic model is well established (Malpezzi, 200 ; Sirmans et al., 2005b; Simons and Saginor, 2006) assuming that certain threshold assumptions are met.[10] The model is used commonly by academics, real estate assessors, appraisers, and realtors when large datasets are available on past residential sales transactions, and when estimates of the marginal impact of certain house characteristics and other factors on sales prices are desired.[11]

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[10] These assumptions, which are discussed in greater detail in Section 4.2 and Appendix , include absence of outliers and/or influencers, presence of homoskedastic variances, absence of spatial and temporal autocorrelation, and absence of collinearity between the variables of interest and other independent variables.

[11] It should be emphasized that a hedonic model is not designed to appraise properties (i.e., to establish an estimate of the market value of a home at a specified point in time), as would be done with an automated valuation model (A M). ather, hedonic models are designed to estimate the marginal contribution of individual house or community characteristics to sales prices, which requires hedonic models to rely upon large data sets with a sizable number of explanatory variables. Appraisal models, on the other hand, are generally based on small, localized data sets (i.e., comps) and a limited number of explanatory variables that pertain to nearby properties. ue to their higher level of accuracy through the use of significantly more information (e.g., diverse spatial, temporal, and

A particularly useful application of the hedonic regression model is to value non-market goods – goods that do not have transparent and observable market prices. For this reason, the hedonic model is often used to derive value estimates of amenities such as wetlands (e.g., Mahan et al., 2000) or lake views (e.g., Seiler et al., 2001), and disamenities, such as proximity to and/or views of high-voltage transmission lines (H TLs) (e.g. es- osiers, 2002), fossil fuel power plants (avis, 2008), roads (e.g. Bateman et al., 2001), cell phone towers (e.g. Bond and Wang, 2007), and landfills (e.g., Thayer et al., 1992; eady and Abdalla, 2005).

There are a number of useful reviews that describe the application of hedonic models in these circumstances (Kroll and Priestley, 1992; Farber, 1998; McCann, 1999; Bateman et al., 2001; Boyle and Kiel, 2001; Jackson, 2001; eady and Abdalla, 2005; Simons and Saginor, 2006; Simons, 2006b; Leonard et al., 2008).[12] The large number of studies covered in these reviews demonstrate that hedonic models are regularly used to investigate the interplay between home values and distance to potential disamenities, teasing out if and how sales prices are adversely affected depending on the distance of a typical home from a disamenity. For example, Carroll et al. (1996) use a hedonic model to estimate a devaluation of 16 for homes close to a chemical plant, with a 6.5 increase in sales price per mile away out to 2.5 miles, at which point effects fade entirely. ale et al. (1999) find a maximum effect of -4 near a lead smelter, with sales prices increasing 2 for each mile away out to two miles, where effects again fade. eady and Abdalla (2005) find maximum effects near landfills of -12.4 , which fade entirely outside 2,400 feet, and maximum effects near confined animal feeding operations of -6.4 , which fade entirely outside of 1,600 feet. Meanwhile, studies of other energy infrastructure, such as H TLs, find maximum effects of -5.7 for homes adjacent to a H TL tower, and an increase in prices of 0.018 per foot away from the tower out to 00 feet (Hamilton and Schwann, 1995), and maximum effects of -14 for homes within 50 feet of a H TL, but no effect for similar homes at 150 feet (es- osiers, 2002). Further, for fossil fuel power plants, avis (2008) finds average adverse effects of between and 5 inside of two miles but that those effects fade entirely outside of that distance range.

In addition to investigating how sales prices change with distance to a disamenity, hedonic models have been used to investigate how prices have changed over time. For instance, sales prices have sometimes been found to rebound after the removal of a disamenity, such as a lead smelter (ale et al., 1999), or to fade over time, as with H TLs (Kroll and Priestley, 1992) or spent fuel storage facilities (Clark and Allison, 1999). Finally, hedonic models have been used to estimate how views of a disamenity affect sales prices. es- osiers (2002), for example, finds that homes adjacent to a power line and facing a H TL tower sell for as much as 20 less than similar homes that are not facing a H TL tower.

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characteristic information) and rigorous methodology, hedonic models can also be used as appraisal models. Automated valuation models cannot, however, be reliably used to measure marginal effects because they do not employ sufficient information to do so, and, more importantly, A Ms do not hold controlling characteristics constant, which could bias any resulting estimates of marginal effects.

[12] For further discussion of the hedonic model and its application to the quantification of environmental stigmas in comparison to other methods see Jackson (2005).

It is unclear how well the existing hedonic literature on other disamenities applies to wind turbines, but there are likely some similarities. For instance, in general, the existing literature seems to suggest that concerns about lasting health effects provide the largest diminution in sales prices, followed by concerns for one s enjoyment of the property, such as auditory and visual nuisances, and that all effects tend to fade with distance to the disamenity - as the perturbation becomes less annoying. This might indicate that property value effects from wind turbines are likely to be the most pronounced quite close to them, but fade quickly as their auditory and visual impacts fade. The existing hedonic literature also, in general, finds that effects fade with time as self-selecting buyers without prejudice towards the disamenity move into the area, or as the real or perceived risks of the disamenity are lessoned (Jackson, 2001). This implies that any stigmas related to wind turbines might also fade over time as local communities come to accept their presence.

2.2. Impacts of Wind Projects on Property Values

Turning to the literature that has investigated the potential property value effects from wind facilities directly, it deserves note that few studies have been academically peer-reviewed and published; in some cases, the work has been performed for a party on one side or the other of the permitting process (e.g., the wind developer or an opposition group). onetheless, at a minimum, a brief review of this existing literature will set the stage for and motivate the later discussion of the methods and results of the present work. The literature described below is summarized in Table 1. To frame this discussion, where possible, the three potential stigmas discussed earlier are used:

- Area Stigma: A concern that the general area surrounding a wind energy facility will appear more developed, which may adversely affect home values in the local community regardless of whether any individual home has a view of the wind turbines.
- Scenic ista Stigma: A concern that a home may be devalued because of the view of a wind energy facility, and the potential impact of that view on an otherwise scenic vista.
- uisance Stigma: A concern that factors that may occur in close proximity to wind turbines, such as sound and shadow flicker, will have a unique adverse influence on home values.

In one of the most recent studies, Sims et al. (2008) used a hedonic model to investigate Scenic ista Stigma using 199 residential transactions within of a mile of the 16-turbine Bears own wind facility in Cornwall, UK. They found both large positive and smaller negative significant relationships between views of the turbines and sales prices depending on whether the view is seen from the front or rear of the home, respectively, but found no relationship between the number of wind turbines visible and sales prices. Previously, Sims and ent (2007) used a hedonic model to investigate uisance and Scenic ista Stigma with 919 transactions for homes within five miles of two wind facilities in the UK, finding only limited evidence of a relationship between proximity to and views of turbines and sales prices, which local real estate experts attributed to other causes. Hoen (2006) investigated Scenic ista Stigma using a hedonic model to analyze 280 residential transactions occurring near a wind facility in Madison County, , and found no evidence that views of turbines significantly affects prices. Jordal-Jorgensen (1996) investigated uisance Stigma in enmark, and found an adverse effect for homes located close to the turbines, but no statistical significance was reported.[1]

[1] A copy of this report could not be obtained and therefore its findings are reported based on other citations.

Using different statistical methods, Poletti (2005; 2007) used a *t*-Test to investigate uisance and Area Stigma by comparing the mean sales prices of 187 and 256 homes in Illinois and Wisconsin, respectively, located near wind facilities (target group) to those further away (control group).[14, 15] He split these target and control groups into respective smaller and more-homogenous sub-groups, such as large and small tracts, with and without homes, finding no statistical evidence that homes near the wind facilities sold for different prices than those farther away. Sterzinger et al. (200) analyzed roughly 24,000 residential transactions, which were divided between those within five miles of a wind facility and those outside of five miles in an effort to assess Area Stigma. They compared residential appreciation rates over time, and found no apparent difference between those homes within and outside of five miles from a wind facility, but the statistical significance of this comparison was not reported.

ther authors have used smaller samples of residential transactions and a variety of simple statistical techniques, without reporting statistical significance, and have found a lack of evidence of effects from uisance Stigma (Jerabek, 2001; Jerabek, 2002; Beck, 2004) and Area Stigma (eLacy, 2005; oldman, 2006). These results, however, are somewhat contrary to what one appraiser has found. In his investigation of uisance Stigma around a wind facility in Lee County, IL, McCann (2008) found that two homes nearby a wind facility had lengthy selling periods that, he believes, also adversely affected transaction prices. Additionally, Kielisch (2009) investigated uisance Stigma by comparing twelve transactions of undeveloped land near two wind facilities in Wisconsin (Blue Sky reen Field and Forward) to undeveloped land transactions farther away. He found that land tracts near the wind facilities sold for dramatically lower prices (/acre) than the comparable group, but the statistical significance of the comparison was not reported.

In addition to these revealed preference studies, a number of stated preference surveys (e.g., contingent valuation) and general opinion surveys have investigated the existence of potential effects.[16] A survey of <u>local residents</u>, conducted after the wind facilities were erected, found no evidence of Area Stigma (oldman, 2006), while another found limited evidence of these stigmas (Bond, 2008).[17] Similarly, some surveys of <u>real estate experts</u> conducted after facility

[14] A *t*-Test is used to compare two sample means by discerning if one is significantly different from the other.

[15] The 2007 study used the data contained in the 2005 study in combination with new data consisting of transactions that occurred in the interim period.

[16] Contingent valuation is a survey based technique to value non-market goods (e.g., an environmental disamenity) that asks respondents what their willingness to pay (or willingness to accept) is to have, for instance, a disamenity removed from (or to have it remain in) their neighborhood. This technique is distinct from a general opinion survey, which might ask whether respondents believe property values have been impacted by an environmental disamenity and, if so, by how much. Although there are important distinctions between the two techniques, with the contingent valuation method often preferred by economic practitioners, for simplicity no distinction is made here between these two approaches. Finally, another subset of the survey literature focuses on public acceptance (i.e., opinion). Though these public acceptance surveys sometimes cover possible impacts on property values, those impacts are not quantified in economic terms. As a result, public acceptance survey results are not reported here.

[17] Bond (2008) asked respondents to declare if the wind facility, which is located roughly 7 miles away, would effect what they would be willing to pay for their house and 75 said either they would pay the same or more for their house, while the remainder would pay less. When those latter respondents were asked to estimate the percentage difference in value, their estimates averaged roughly 5 .

construction have found no evidence of Area or uisance Stigmas (rover, 2002; oldman, 2006). These results, however, are contrary to the expectations for Area, Scenic ista, and uisance Stigma effects predicted by local residents (Haughton et al., 2004; Firestone et al., 2007) and real estate experts (Haughton et al., 2004; Khatri, 2004; Kielisch, 2009) prior to construction found elsewhere.[18] The difference between predicted and actual effects might be attributable, at least in part, to the fear of the unknown. For instance, Wolsink (1989) found that public attitudes toward wind power, on average, are at their lowest for local residents during the wind project planning stage, but return almost to pre-announcement levels after the facilities are built. This result is echoed by Exeter-Enterprises-Ltd. (199) and Palmer (1997), whose post-construction surveys found higher approval than those conducted pre-construction. thers, however, have found that perceptions do not always improve, attributing the lack of improvement to the perceived success or lack therefore of the project, with strong disapproval forming if turbines sit idle (Thayer and Freeman, 1987) or are perceived as a waste of taxpayer dollars (evine-Wright, 2004).

When this literature is looked at as a whole, it appears as if wind projects have been predicted to negatively impact residential property values when pre-construction surveys are conducted, but that sizable, widespread, and statistically significant negative impacts have largely failed to materialize post-construction when actual transaction data become available for analysis. The studies that have investigated Area Stigma with market data have failed to uncover any pervasive effect. f the studies focused on Scenic ista and uisance Stigmas, only one is known to have found statistically significant adverse effects, yet the authors contend that those effects are likely driven by variables omitted from their analysis (Sims and ent, 2007). ther studies that have relied on market data have sometimes found the possibility of negative effects, but the statistical significance of those results have rarely been reported.

espite these findings, the existing literature leaves much to be desired. First, many studies have relied on surveys of homeowners or real estate professionals, rather than trying to quantify real price impacts based on market data. Second, a number of studies conducted rather simplified analyses of the underlying data, potentially not controlling for the many drivers of residential sales prices. Third, many of the studies have relied upon a very limited number of residential sales transactions, and therefore may not have had an adequate sample to statistically discern any property value effects, even if effects did exist. Fourth, and perhaps as a result, many of the studies did not conduct, or at least have not published, the statistical significance of their results. Fifth, when analyzed, there has been some emphasis on Area Stigma, and none of the studies have investigated all three possible stigmas simultaneously. Sixth, only a few of the studies (Hoen, 2006; Sims and ent, 2007; Sims et al., 2008; Kielisch, 2009) conducted field visits to the homes to assess the quality of the scenic vista from the home, and the degree to which the wind facility might impact that scenic vista. Finally, with two exceptions (Sims and ent, 2007; Sims et al., 2008), none of the studies have been academically peer-reviewed and published.

[18] It should be noted that the samples used by both Khatri and Kielisch contained a subset of respondents who did have some familiarity with valuing homes near wind facilities.

Table 1: Summary of Existing Literature on Impacts of Wind Projects on Property Values

Document Type Author(s)	Year	Number of Transactions or Respondents	Before or After Wind Facility Construction Commenced	Area Stigma	Scenic Vista Stigma	Nuisance Stigma
Homeowner Survey						
Haughton et al.	2004	501	Before	-	-	
oldman	2006	50	After	**none**		
Firestone et al.	2007	504	Before	-	-	
Bond	2008	00	After		-	-
Expert Survey						
rover	2002	1	After	**none**		**none**
Haughton et al.	2004	45	Before	-	-	
Khatri	2004	405	Before‡	-		-
oldman	2006	50	After	**none**		**none**
Kielisch	2009	57	Before‡			-
Transaction Analysis - Simple Statistics						
Jerabek	2001	25	After			**none**
Jerabek	2002	7	After			**none**
Sterzinger et al.	200	24,000	After	**none**		
Beck	2004	2	After			**none**
Poletti	2005	187	After	**none**		**none**
eLacy	2005	21	Before	**none**		
oldman	2006	4	After	**none**		
Poletti	2007	256	After	**none**		**none**
McCann	2008	2	After			-
Kielisch	2009	10	After			-
Transaction Analysis - Hedonic Model						
Jordal-Jorgensen	1996		After			-
Hoen	2006	280	After		**none**	
Sims ent	2007	919	After			-
Sims et al.	2008	199	After		-/	

" none " indicates the majority of the respondents do not believe properties have been affected (for surveys) or that no effect was detected at 10% significance level (for transaction analysis)

- *indicates a negative effect without statistical significance provided*

- *indicates statistically significant negative effect at 10% significance level*

-/ *indicates positive and negative statistically significant effects at 10% significance level*

Sales were collected after facility announcement but before construction

‡ *Some respondents had experience with valuations near facilities while others did not*

3. Data Overview

The methods applied in the present work are intended to overcome many of the limitations of the existing literature. First, a large amount of data is collected from residential transactions within 10 miles of 24 different wind projects in the U.S., allowing for a robust statistical analysis across a pooled dataset that includes a diverse group of wind project sites. Second, all three potential stigmas are investigated by exploring the potential impact of wind projects on home values based both on the distance to and view of the projects from the homes. Third, field visits are made to every home in the sample, allowing for a solid assessment of the scenic vista enjoyed by each home and the degree to which the wind facility can be seen from the home, and to collect other value-influencing data from the field (e.g., if the home is situated on a cul-de-sac). Finally, a number of hedonic regression models are applied to the resulting dataset, as are repeat sales and sales volume analyses, in order to assess the robustness of the results.

Testing for the three potential stigmas requires a significant sample of residential transactions within close proximity to existing wind facilities. Unfortunately for the study, most wind power projects are not located near densely populated areas. As a result, finding a single wind project site with enough transaction data to rigorously analyze was not possible. Instead, the approach was to collect data from multiple wind project sites, with the resulting data then pooled together to allow for robust statistical analyses.[19] The remainder of this section describes the site selection process that is used, and provides a brief overview of both the selected study areas and the data that were collected from these areas. Also provided is a description of how scenic vista, views of turbines, and distances from turbines were quantified for use in the hedonic analysis, and a summary of the field data collection effort. The section ends with a brief summary of the resulting dataset.

3.1. Site Selection

For the purpose of this study, an ideal wind project area would:

1) Have a large number of residential transactions both before and, more importantly, after wind facility construction, and especially in close proximity (e.g., within 2 miles) of the facility;
2) Have comprehensive data on home characteristics, sales prices, and locations that are readily available in electronic form; and
) Be reasonably representative of the types of wind power projects being installed in the United States.

To identify appropriate sites that met these criteria, and that also provided a diversity of locations, the authors obtained from Energy elocity, LLC a set of eographic Information System (IS) coordinates representing 241 wind projects in the U.S. that each had a total nameplate capacity greater than 0.6 megawatts (MW) and had gone online before 2006.[20] Also provided were facility capacity, number of turbines, and announcement, construction, and operational dates. These data were cross-checked with a similar dataset provided by the American Wind Energy Association (AWEA), which also included some turbine hub-height information.

[19] A thorough discussion of this pooled approach is contained in Section 4.2 and in Appendix F.

[20] Energy elocity, LLC was owned at the time by lobal Energy ecisions, which was later purchased by entyx. The dataset is available as elocity Suite 2008 from entyx.

By using a variety of different IS sorting techniques involving nearby towns with populations greater than, for example, 2,500 people, using census tract population densities, and having discussions with wind energy stakeholders, a prospective list of 56 possible study areas was generated, which were then ranked using two scales: highly desirable to least desirable, and feasible to potentially unfeasible. [21] Then, through an iterative process that combined calls to county officials to discuss the number of residential transactions and data availability, with investigations using mapping software to find the location of individual wind turbines, and, in some cases, preliminary visits, a list of 17 prospective study areas were chosen as both highly desirable and feasible. Ultimately, three of these proved to be unfeasible because of data availability issues and four undesirable because the study area was considered not representative. This effort ultimately resulted in a final set of ten study areas that encompass a total of 24 distinct wind facilities (see Figure 1 and Table 2).[22] A full description of each study area is provided in Appendix A.

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[21] esirability was a combination of a number of factors: the wind facility having more than one turbine; the study area having greater than 50 sales within 5 miles and within 10 years, 250 of which transacted following construction of the facility; having some transaction data old enough to pre-date facility announcement; having data on the core home and site characteristics (e.g., square feet, acres); and, where possible, having a concentration of sales within 1 mile of the facility. Feasibility was also a combination of factors: having home characteristic and sales data in electronic form; having IS shapefiles of the parcel locations; and being granted ready access to this information.

[22] The unfeasible study areas were Cerro ordo County, IA, Bennington County, T, and Atlantic County, J. Cerro ordo County, IA contained multiple wind projects totaling 140 MW. Although the data at this site were available in electronic form, the county only agreed to share data in paper form, which would have created an enormous data entry burden. Because another site in the sample was considered similar to the Cerro ordo site (IAB), Cerro ordo County was dropped from the prospective sites. Bennington County, T contained the 11 turbine Searsburg Wind Project (6 MW) but had no electronic records. Atlantic County, J contained the five turbine Jersey Atlantic Wind Farm (7.5 MW), but had data in paper records only and the county was unresponsive to inquiries regarding the study. The undesirable study areas were Plymouth County, MA, Wood County, H, Cascade County, MT, and iverside County, CA. Although the data in Plymouth County, MA were more than adequate, this small, on-land, yet coastal Hull Wind facility (2 turbines, 2.5 MW) was not considered to be particularly representative of wind development across the US. Wood County s four turbine Bowling reen facility (7 MW) met the appropriate data requirements, but ultimately it was decided that this facility was too small and remote to be representative. Cascade County s six turbine Horseshoe Bend Wind Park (9 MW) did not have enough transactions to justify study. iverside, CA, where roughly 2500 turbines are located, had less-than-desired home characteristic data, had transactions that came more than 10 years after large scale development began, and despite having homes that were within 1 mile of the turbines, those homes typically had limited views because of high subdivision walls.

Figure 1: Map of Study Areas and Potential Study Areas

Table 2: Summary of Study Areas

Study Area Code	Study Area Counties, States	Facility Names	Number of Turbines	Number of MW	Max Hub Height (meters)	Max Hub Height (feet)
WAOR	Benton and Walla Walla Counties, WA and Umatilla County,	ansycle idge, Stateline, ine Canyon I II, Combine Hills	582	429	60	197
TXHC	Howard County, T	Big Spring I II	46	4	80	262
OKCC	Custer County, K	Weatherford I II	98	147	80	262
IABV	Buena ista County, IA	Storm Lake I II, Waverly, Intrepid I II	81	70	65	21
ILLC	Lee County, IL	Mendota Hills, S Wind	10	1 0	78	256
WIKCDC	Kewaunee and oor Counties, WI	ed iver, Lincoln	1	20	65	21
PASC	Somerset County, PA	reen Mountain, Somerset, Meyersdale	4	49	80	262
PAWC	Wayne County, PA	Waymart	4	65	65	21
NYMCOC	Madison and neida Counties,	Madison	7	12	67	220
NYMC	Madison County,	Fenner	20	0	66	218
		TOTAL	**1345**	**1286**		

These 10 study areas and 24 projects are located in nine separate states, and include projects in the Pacific orthwest, upper Midwest, the ortheast, and the South Central region. The wind projects included in the sample total 1,286 MW, or roughly 1 of total U.S. wind power capacity installed at the time (the end of 2005). Turbine hub heights in the sample range from a

minimum of 164 feet (50 meters) in the Washington/ regon (WA) study area, to a maximum of 262 (80 meters) (T HC, KCC and PASC), with nine of the ten study areas having hub heights of at least 21 feet (65 meters). The sites include a diverse variety of land types, including combinations of ridgeline (WA , PASC, and PAWC), rolling hills (ILLC, WIKC C, MC C, and MC), mesa (T HC), and windswept plains (KCC, IAB).[2]

3.2. Data Collection

In general, for each study area, residential transaction data in as close proximity to the wind turbines as possible was sought, from both before and after wind facility construction. To balance the cost and quantity of data collection in each study area with the desire to cover as many study areas as possible, the research effort sought to collect data on 400 to 1,250 transactions in each study area.[24] In some instances, this meant including all residential transactions within ten miles of the wind turbines. In others, only transactions within five miles were included. In some extreme instances, when the number of transactions inside of five miles far exceeded the 1,250 limit, all transactions in close proximity to the wind turbines (e.g., inside three miles) were included in combination with a random sample of transactions outside of that distance band (e.g., between three and five miles).[25] The data selection processes for each Study Area are contained in Appendix A.

Three primary sets of data are used in the analysis: tabular data, IS data, and field data, each of which is discussed below. Following that, this subsection highlights the two qualitative variables that are essential to this analysis and that therefore require special attention, scenic vista and views of turbines, and then discusses the field data collection process.

3.2.1. Tabular Data

Berkeley Lab obtained tabular transaction data from participating counties[26] containing 7,459 valid [27] transactions of single family residential homes, on less than 25 acres,[28] which were

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[2] Some areas, such as PASC, had both a ridgeline and rolling hills on which wind facilities were located.

[24] This range was chosen to ensure that a minimum of data were present in each study area to allow for a robust analysis, and yet not too much so as to make data collection (e.g., the visiting of each home) inordinately time and resource consuming in any individual study area.

[25] An alternative method would have been to collect data on every sale that occurred. Although in most cases this would be preferred, in ours it would not have added one additional transaction within close proximity or with dramatic views of wind turbine, the focus of the study. ather, it would have added an overwhelming majority of transactions of homes without views and at distances outside of three miles from the turbines, all of which would have come at considerably cost and, more importantly, would not likely have influenced the results significantly while perhaps necessitating a reduction in the total number of study areas that could be included in the sample.

[26] In some cases, the county officials, themselves, extracted data from their database, and in some cases a company engaged to manage a county s data provided the necessary information. In either case the provider is referred to as county. etailed descriptions of the providers are presented in Appendix A.

[27] alidity was determined by each individual county data provider. A sale that is considered valid for county purposes would normally meet the minimum requirements of being arm s length; being a transfer of all rights and warrants associated with the real estate; containing an insignificant amount of personal property so as not to affect the price; demonstrating that neither party in the sale acting under duress or coercion; not being the result of a liquidation of assets or any other auction, a mortgage foreclosure, a tax sale, or a quit claim; and being appropriate for use in calculating the sales price to assessed value ratios that are reported to the state. ue to the formal requirements associated with this calculation, validity is often defined by a state s epartment of evenue, as shown, for example, here: http://www.orps.state.ny.us/assessor/manuals/vol6/rfv/index.htm. In addition, though the

sold for a price of more than 10,000,[29] which occurred after January 1, 1996, [0] and which had fully populated core home characteristics. These core characteristics are: number of square feet of the living area (not including finished basement), acres of land, bathrooms, and fireplaces, the year the home was built, [1] if the home had exterior wallsthatwere stone, a central air conditioning unit, and/or a finished basement, and the exterior condition of the home. The 7,459 residential transactions in the sample consist of 6,194 homes (a number of the homes in the sample sold more than once in the selected study period). Because each transaction had a corresponding set of the core home characteristic data, they could all be pooled into a single model. In addition to the home characteristic data, each county provided, at a minimum, the home s physical address and sales price. The counties often also provided data on homes in the study area that did not sell in the study period. [2] Finally, market-specific quarterly housing inflation indexes were obtained from Freddie Mac, which allowed nominal sales prices to be adjusted to 1996 dollars.

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sample originally contained 7,498 sales, 4 homes sold twice in a 6 month period and, after discussions with local officials, these transactions were considered likely to have been invalid despite the county coding them to the contrary. Additionally, five transactions produced standardized residuals that were more than six standard deviations away from the mean, indicating that these sales were abnormal and likely not valid. Both of these sets of transactions, totaling 9, were removed from the final dataset. f the 9 sales, 2 sold following construction, 10 were concentrated in IAB and nine in T HC with the others spread between seven of the remaining eight study areas. ne of the homes was inside of one mile from the turbines at the time of sale, and two had views of the turbines (both of which were MI). The home that was located within one mile was surrounded by a number of other homes – at similar distances from the turbines - that transacted both before and after the wind facilities were built and were included in the sample. A more thorough discussion of the screening techniques used to ensure the appropriateness of the final data set are presented in detail in Appendix under utliers/Influencers. Finally, it should be noted that the authors are aware of four instances in the study areas when homes were sold to wind developers. In two cases the developer did not resell the home; in the other two, the developer resold the home at a lower price than which it was purchased. But, because the sales were to a related party, these transactions were not considered valid and are therefore not included here. ne might, however, reasonably expect that the property values of these homes were impacted by the presence of the wind turbines.

[28] Single family residences on more than 25 acres were considered to be likely candidates for alternative uses, such as agricultural and recreational, which could have an influence on sales price that was outside of the capabilities of the model to estimate. Because all records were for parcels that contained a residence, the model did not contain any land-only transactions. Further, none of the transactions provided for this research were for parcels on which a turbine was located.

[29] A sales price of 10,000 was considered the absolute minimum amount an improved parcel (one containing a residential structure) would sell for in any of the study areas and study periods. This provided an additional screen over and above the valid screen that the counties performed.

[0] This provided a maximum of 12 years of data. Some counties did not have accessible data back to 1996 but in all cases these countries had data on transactions that occurred before the wind facilities were erected.

[1] ear Built was used to construct a variable for the age of the home at the time of the sale.

[2] These data were used to calculate the Sales olume percentages referred to in Section 7.

Freddie Mac Conventional Mortgage Home Price Index: municipal statistical area (MSA) series data are available from the following site: http://www.freddiemac.com/finance/cmhpi/. Because most of the study areas do not fall within the MSAs, a collection of local experts was relied upon, including real estate agents, assessors, and appraisers, to decide which MSA most-closely matched that of the local market. In all cases the experts had consensus as to the best MSA to use. In one case (MC C) the sample was split between two MSAs. These indexes are adjusted quarterly, and span the entire sample period. Therefore, during the housing boom, insofar as a boom occurred in the sample areas, the indexes increased in value. Subsequently when the market began falling, the index retracted.

3.2.2. GIS Data

IS data on parcel location and shape were also required, and were obtained from the counties. The counties also often provided IS layers for roads, water courses, water bodies, wind turbines (in some cases), house locations, and school district and township/town/village delineations.

IS data on census tract and school district delineations were obtained from the U.S. Census Bureau, if not provided by the county. [4] IS data were obtained on water courses, water bodies, land elevations, and satellite imagery, as was necessary, from the U.S. epartment of Agriculture. [5] Combined, these data allowed each home to be identified in the field, the construction of a IS layer of wind turbine locations for each facility, and the calculation of the distance from each home to the nearest wind turbine. [6] etermining the distance from each home to the nearest wind turbine was a somewhat involved process, and is discussed in detail in Appendix B. Suffice it to say that each transaction had a unique distance (ISTA CE) [7] that was determined as the distance between the home and nearest wind turbine at the time of sale, and that these distances are grouped into five categories: inside of 000 feet (0.57 miles), between 000 feet and one mile, between one and three miles, between three and five miles, and outside of five miles. [8] Finally, the IS data were used to discern if the home was situated on a cul-de-sac and had water frontage, both of which were corroborated in the field.

3.2.3. Field Data

Additional data had to be collected through field visits to all homes in the sample. Two qualitative measures in particular – for scenic vista and for view of the wind turbines – are worth discussing in detail because each is essential to the analysis and each required some amount of professional judgment in its creation.

The impact or severity of the view of wind turbines (IEW) [9] may be related to some combination of the number of turbines that are visible, the amount of each turbine that is visible (e.g., just the tips of the blades or all of the blades and the tower), the distance to the nearest turbines, the direction that the turbines are arrayed in relation to the viewer (e.g., parallel or perpendicular), the contrast of the turbines to their background, and the degree to which the turbine arrays are harmoniously placed into the landscape (ipe, 2002). ecent efforts have made some progress in developing quantitative measures of the aesthetic impacts of wind turbines (Torres-Sibillea et al., 2009),[40] but, at the time this project began, few measures had

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[4] These data were sourced from the U.S. Census Bureau s Cartographic Boundary Files Webpage: http://www.census.gov/geo/www/cob/bdy_files.html.

[5] These data were sourced from the US A eospatial ata ateway: http://datagateway.nrcs.usda.gov/ atewayHome.html.

[6] Although in some cases the county provided a IS layer containing wind turbine points, often this was not available. A description of the turbine mapping process is provided in Appendix B.

[7] istance measures are collectively and individually referred to as ISTA CE from this point forward.

[8] The minimum distance of inside 000 feet was chosen because it was the closest cutoff that still provided an ample supply of data for analysis.

[9] iew of turbines ratings are collectively and individually referred to as IEW from this point forward.

[40] In addition to these possible field techniques, previous studies have attempted to use IS to estimate wind turbine visibility using line-of-sight algorithms. For example, Hoen (2006) used these algorithms after adding ground cover to the underlying elevation layer. He found that the IS method differed substantially from the data collected in the field. Seemingly, small inaccuracies in the underlying elevation model, errors in the software s algorithm, and the existence of ground cover not fully accounted for in the IS, substantially biased IS-based assessments of

been developed, and what had been developed was difficult to apply in the field (e.g., Bishop, 2002). As a result, the authors opted to develop an ordered qualitative IEW rating system that consisted of placing the view of turbines into one of five possible categories: IEW, MI , M E ATE, SUBSTA TIAL, and E T EME. These ratings were developed to encompass considerations of distance, number of turbines visible, and viewing angle into one ordered categorical scale, and each rating is defined in Table :[41]

Table 3: Definition of VIEW Categories

IEW	The turbines are not visible at all from this home.
MI IEW	The turbines are visible, but the scope (viewing angle) is narrow, there are many obstructions, or the distance between the home and the facility is large.
M E ATE IEW	The turbines are visible, but the scope is either narrow or medium, there might be some obstructions, and the distance between the home and the facility is most likely a few miles.
SUBSTA TIAL IEW	The turbines are dramatically visible from the home. The turbines are likely visible in a wide scope and most likely the distance between the home and the facility is short.
E T EME IEW	This rating is reserved for sites that are unmistakably dominated by the presence of the wind facility. The turbines are dramatically visible from the home and there is a looming quality to their placement. The turbines are often visible in a wide scope or the distance to the facility is very small.

Photographic examples of each of the categories are contained in Appendix E.

visibility. This was corroborated elsewhere by Maloy and ean (2001) and iggs and ean (2007). As a result of these findings, it was determined that field collection of IEW data was essential.

[41]In addition to the qualitative rating system that was ultimately used in this study, a variety of quantitative data were collected that might describe the nature of the view of wind turbines, including the total number of turbines visible, the distance of the home to the nearest wind turbine, and the view scope/viewing angle (i.e., the degree to which the turbines spread out in front of the home: narrow, medium, or wide). To explore the validity of the qualitative rating scale two tests were conducted. First, a pre-study survey was conducted by showing 10 different off-site respondents 15 randomly selected photographs from the field representing the various rated IEW categories. The higher IEW ratings were oversampled to create a roughly equal distribution among the categories. The respondents rated the views into one of the qualitative categories. The on-site / field collected ratings matched the off-site responses 65 of the time, with 97 of the rankings differing by no more than one category. inety-eight percent of the on-site-ranked MI IEWs and 89 of the E T EME IEWs were similarly ranked by off-site respondents. The on-site rankings were less than the off-site rankings 97 of the time; it is assumed that this is because on-site ratings took into account a greater portion of the panorama than were captured in the photos, which translated into a lower ranking. Secondly, a post hoc Multinomial Logistic egression model was created that used the qualitative on-site IEW ratings as the dependent variable and the quantitative measures of distance to nearest turbine, number of turbines visible, and view scope as the independent variables. This model produced high Pseudo ^{2} statistics (Cox and Snell 0.88, agelkerke 0.95, and McFadden 0.79) and predicted values that were highly correlated with the actual qualitative rating (Pearson s 0.88). Therefore, both tests corroborated the appropriateness of the simpler qualitative IEW rankings used herein.

In addition to the qualitative IEW measurements, a rating for the quality of the scenic vista (ISTA)[42] from each home, absent the existence of the wind facilities, was also collected in the field. An assessment of the quality of the ISTA from each home was needed because IEW and ISTA are expected to be correlated; for example, homes with a P EMIUM ISTA are more likely to have a wide viewing angle in which wind turbines might also be seen. Therefore, to accurately measure the impacts of the IEW of wind turbines on property values a concurrent control for ISTA (independent of any views of turbines) is required. rawing heavily on the landscape-quality rating system developed by Buhyoff et al. (1994) and to a lesser degree on the systems described by others (aniel and Boster, 1976; US A, 1995), an ordered ISTA rating system consisting of five categories was developed: P , BEL W A E A E, A E A E, AB E A E A E, and P EMIUM, with each rating defined in Table 4:[4]

Table 4: Definition of VISTA Categories

P ISTA	These vistas are often dominated by visually discordant man-made alterations (not considering turbines), or are uncomfortable spaces for people, lack interest, or have virtually no recreational potential.
BEL W A E A E ISTA	These scenic vistas contain visually discordant man-made alterations (not considering turbines) but are not dominated by them. They are not inviting spaces for people, but are not uncomfortable. They have little interest or mystery and have minor recreational potential.
A E A E ISTA	These scenic vistas include interesting views that can be enjoyed often only in a narrow scope. These vistas may contain some visually discordant man-made alterations (not considering turbines), are moderately comfortable spaces for people, have some interest, and have minor recreational potential.
AB E A E A E ISTA	These scenic vistas include interesting views that often can be enjoyed in a medium to wide scope. They might contain some man-made alterations (not considering turbines), yet still possess significant interest and mystery, are moderately balanced and have some potential for recreation.
P EMIUM ISTA	These scenic vistas would include picture postcard views that can be enjoyed in a wide scope. They are often free or largely free of any discordant man made alterations (not considering turbines), possess significant interest, memorable qualities, and mystery and are well balanced and likely have a high potential for recreation.

Photographic examples of each of the categories are contained in Appendix D.

[42] Scenic vista ratings are individually and collectively referred to as ISTA from this point forward.

[4] The appropriateness of these rankings were tested in two ways. First, a set of 4 pictures taken on-site and representing various categories of ISTA were shown to 10 off-site respondents who were asked to rank them using the same categories, and then explain why they rated them as such. Although the off-site ratings matched the on-site ratings only 51 of the time, 94 of on- and off-site rankings differed by no more than one category, with 17 of the off-site rankings below the on-site and 26 ranked above. The descriptions of why the rankings where chosen by the off-site respondents illuminated the fact that off-site ratings did not take into account a number of aspects that were not adequately captured in the photos, but that were apparent in the field. This finding was borne out by a second test that had five individuals visit seven homes in the field to rank their scenic vistas. When all respondents were on-site, they similarly ranked the vista 72 of the time, with a rankingthat differed by no more than one category occurring one hundred percent of the time.

In addition to the IEW and ISTA ratings, it was assumed that the orientation of the home to the view of turbines (e.g., front, back, or side) (IE TATI), and the degree to which the view of the turbines overlapped the primary scenic vista (e.g., not at all, barely, somewhat or strongly) (E LAP), might influence residential property values. As such, information on IE TATI and E LAP were also collected in the field.

3.2.4. Field Data Collection

Field data collection was conducted on a house-by-house basis. Each of the 6,194 homes was visited by the same individual to remove bias among field ratings. ata collection was conducted in the fall of 2006, and the spring, summer, and fall of 2007 and 2008. Each house was photographed and, when appropriate, so too were views of turbines and the prominent scenic vista.[44] ata on IEW were collected only for those homes that sold after at least one wind power facility had been erected in the study area. When multiple wind facilities, with different construction dates, were visible from a home, field ratings for IEW were made by taking into account which turbines had been erected at the time of sale. Additionally, if the season at the time of sale differed from that of data collection and, for example, if leaves were off the trees for one but on for the other, an effort was made to modulate the IEW rating accordingly if necessary.[45]

Both IEW and ISTA field ratings were arrived at through a -Sort method (Pitt and ube, 1979), which is used to distinguish relatively similar rankings. For views of turbines, the rater first determined if the ranking was MI or E T EME. If neither of these two rankings was appropriate, then only a choice between M E ATE and SUBSTA TIAL was required. Similarly, for ISTA rankings, first P and P EMIUM were distinguished from the others; if neither applied then BEL W A E A E or AB E A E A E could be selected. If neither of those were appropriate the ISTA, by default, was considered A E A E. In all cases, if wind turbines were visible from the home, the ISTA rankings were made as if those turbines did not exist.

3.3. Data Summary

The final dataset consists of 7,459 valid and screened residential transactions occurring between January 2, 1996 and June 0, 2007. Those transactions are arrayed across time and the ten wind project study areas as shown in Table 5. The sample of valid residential transactions ranges from 412 in Lee County, Illinois (ILLC) to 1, 11 in Howard County, Texas (T HC).[46] f the total 7,459 transactions, 4,9 7 occurred after construction commenced on the relevant wind facilities. More specifically, 2 of the transactions (n=1,755) took place before any wind facility was announced and 10 occurred after announcement but before construction commenced (n=767),

[44] In many cases the prominent ISTA was homogenous across groups of home, for instance urban homes on the same road. In those cases a picture of the ISTA of one home was applied to all of the homes. All pictures were taken with a Canon E S ebel Ti Single Lens eflex Camera with a 18-55mm lens. IEW and ISTA pictures were taken with the lens set to 18mm, with the camera at head height, and with the center of the camera pointed at the center of the prominent ISTA or IEW. Examples of the various ISTA and IEW categories are contained in Appendices and E respectively.

[45] This modulation occurred only for trees in the foreground, where, for instance, a single tree could obscure the view of turbines; this would not be the case for trees nearer the horizon.

[46] See description of valid in footnote 27 on page 1 .

with the rest of the transactions occurring after construction commenced (66 , *n*=4,9 7).[47] f that latter group, 17 (*n*=824, 11 of total) sold in the first year following the commencement of construction, 16 in the second year (*n*=811, 11 of total), and the remainder (67) sold more than two years after construction commenced (*n*= , 02, 44 of total).

Table 5: Summary of Transactions across Study Areas and Development Periods

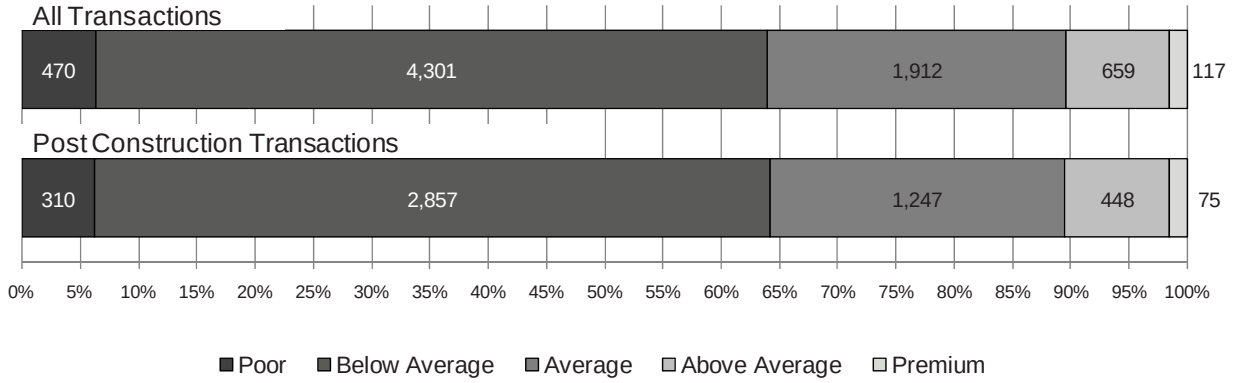
	Pre Announcement	Post Announcement Pre Construction	1st Year After Construction	2nd Year After Construction	2+ Years After Construction	Total
Benton/Walla Walla, WA & Umatilla, OR (WAOR)	226	45	76	59	84	**790**
Howard, TX (TXHC)	169	71	11	1 1	827	**1311**
Custer, OK (OKCC)	484	15	19	187	96	**1113**
Buena Vista, IA (IABV)	152	65	80	70	455	**822**
Lee, IL (ILLC)	115	84	62	71	80	**412**
Kewaunee/Door, WI (WIKCDC)	44	41	68	62	595	**810**
Somerset, PA (PASC)	175	28	46	60	185	**494**
Wayne, PA (PAWC)	22	106	64	71	87	**551**
Madison/Oneida, NY (MYMCOC)	108	9	48	0	268	**463**
Madison, NY (NYMC)	59	165	74	70	25	**693**
TOTAL	**1755**	**767**	**824**	**811**	**3302**	**7459**

A basic summary of the resulting dataset, including the many independent variables used in the hedonic models described later, is contained in Table 6 and Table 7. These tables present summary information for the full dataset (7,459 transactions) as well as the post-construction subset of that dataset (4,9 7 transactions); the latter is provided because much of the analysis that follows focuses on those homes that sold after wind facility construction. The mean nominal residential transaction price in the sample is 102,968, or 79,114 in 1996 dollars. The average house in the sample can be described as follows: it is 46 years old, has 1,620 square feet of finished living area above ground, is situated on 1.1 acres, has 1.74 bathrooms, and has a

[47] The announcement date (as well as construction and online dates) was provided by Energy elocity with the IS files as described in footnote 20 on page 10. The date corresponds to the first time the facility appears in the public record, which was often the permit application date. This constitutes the first well established date when the existing wind facility would have been likely known by the public, and therefore is appropriate to use for this analysis, but there remain a number of areas for potential bias in this date. First, the permit application date might be preceded by news reports of the impending application; alternatively, if the public record was not published online (that Energy elocity used to establish their date), the announcement date – as used here - could, in fact, follow the permit application date. To address this, when possible, the authors had discussions with the developer of the facility. In most cases, the Energy elocity dates were found to be accurate, and when they were not they were adjusted to reflect the dates provided by the developer. A second potential source of bias is the possibility that a different project was proposed but never built, but that influenced the residential market in the study area prior to the announcement date. Although this is likely rarer, we are aware of at least a few projects that fit that description in the study areas. A final source of bias might revolve around the likelihood that awareness of a project could occur even before the facility is formally announced. For example, a community member might know that a wind facility is being considered because they had been approached by the wind development company well ahead of a public announcement. In turn, they might have had private discussions regarding the facility with other members of the community. Taken together, it is appropriate to assume that there is some bias in the announcement date, and that awareness of the project might precede the date used in this analysis. How this bias might affect the results in this report is addressed further in Section 5. and footnote 74 on page 8.

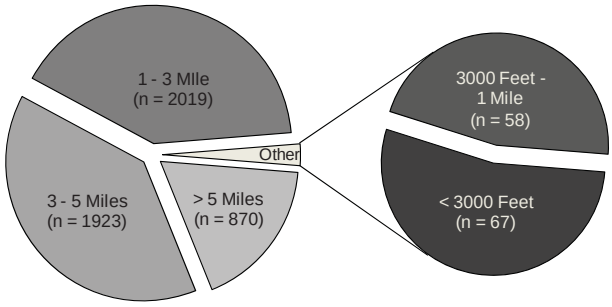
slightly better than average condition.[48] Within the full sample, 6 and 58 of homes had a poor or below average ISTA rating, respectively; 26 of homes received an average rating on this scale, with 9 above average and 2 experiencing premium vistas (see Figure 2).

Figure 2: Frequency of VISTA Ratings for All and Post-Construction Transactions



With respect to the variables of interest, among the post-construction subset of 4,9 7 transactions, the frequency of the ISTA CE categories is found to follow geometry with the smallest numbers of transactions occurring near the wind turbines and ever increasing numbers further away (see Figure). 67 transactions (1) are situated inside of ,000 feet (0.57 Miles), 58 (1) are between ,000 feet and one mile (0.57-1 mile), 2,019 (41) occur outside of one mile but inside of three miles (1- miles), 1,92 (9) occur between three and five miles (-5 miles), and 870 (18) occur outside of five miles (5 miles).[49] In this same post-construction group, a total of 7 0 homes that sold (15) have a view of the wind turbines (see Figure 4). A large majority of those homes have MI view ratings (*n* = 561, 11 of total), with 2 having M E ATE ratings (*n*=106) and the remaining transactions roughly split between SUBSTA TIAL and E T EME ratings (*n*= 5, 0.6 , and *n*=28, 0.5 , respectively). A full description of the variables of interest and how they are arrayed at the study area level is contained in Appendix A.

Figure 3: Frequency of DISTANCE Ratings for Post-Construction Transactions



[48] The variable for the condition of the home was not uniform across study areas because, in some cases, it took into account construction grade while in others it did not.

[49] These numbers and percentages are skewed slightly from the overall population of transactions because homes outside of three miles were often under-sampled to reduce field data collection burdens. Further, higher numbers of homes fall into each of the categories when the post-announcement-pre-construction transactions are included, as they are in some models. These additional transactions are described below in Table 7 under All Sales.

Figure 4: Frequency of VIEW Ratings for Post-Construction Transactions

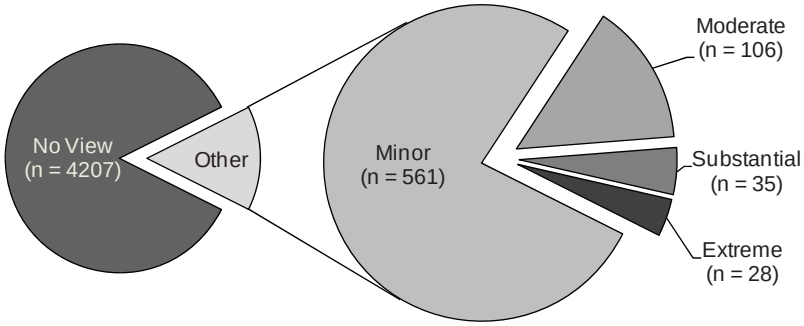


Table 6: Summary Statistics: All Sales and Post-Construction Sales

		All Sales			Post Construction Sales		
Variable Name	**Description**	**Freq. ***	**Mean**	**Std. Dev.**	**Freq. ***	**Mean**	**Std. Dev.**
SalePrice	The unadjusted sale price of the home (in US dollars)	7,459	102,968	64,29	4,9 7	110,166	69,422
SalePrice96	The sale price of the home adjusted to 1996 US dollars	7,459	79,114	47,257	4,9 7	80,156	48,906
LN_SalePrice96	The natural log transformation of the sale price of the home adjusted to 1996 US dollars	7,459	11.12	0.58	4,9 7	11.12	0.60
AgeatSale	The age of the home at the time of sale	7,459	46	7	4,9 7	47	6
AgeatSale_Sqrd	The age of the home at the time of sale squared	7,459	,491	5,410	4,9 7	,506	5,412
Sqft_1000	The number of square feet of above grade finished living area (in 1000s)	7,459	1.62	0.59	4,9 7	1.628	0.589
Acres	The number of Acres sold with the residence	7,459	1.1	2.42	4,9 7	1.10	2.40
Baths	The number of Bathrooms (Full Bath = 1, Half Bath = 0.5)	7,459	1.74	0.69	4,9 7	1.75	0.70
ExtWalls_Stone	If the home has exterior walls of stone, brick or stucco (es = 1, o = 0)	2,287	0. 1	0.46	1,486	0. 0	0.46
CentralAC	If the home has a Central AC unit (es = 1, o = 0)	,785	0.51	0.50	2,575	0.52	0.50
Fireplace	The number of fireplace openings	2,708	0. 9	0.55	1,8 4	0.40	0.55
Cul_De_Sac	If the home is situated on a cul-de-sac (es = 1, o = 0)	990	0.1	0. 4	67	0.14	0. 4
FinBsmt	If finished basement square feet is greater than 50 times first floor square feet (es = 1, o = 0)	1,472	0.20	0.40	992	0.20	0.40
Water_Front	If the home shares a property line with a body of water or river (es = 1, o = 0)	107	0.01	0.12	87	0.02	0.1
Cnd_Low	If the condition of the home is Poor (es = 1, o = 0)	101	0.01	0.12	69	0.01	0.12
Cnd_BAvg	If the condition of the home is Below Average (es = 1, o = 0)	519	0.07	0.25	59	0.07	0.26
Cnd_Avg	If the condition of the home is Average (es = 1, o = 0)	4, 57	0.58	0.49	2,727	0.55	0.50
Cnd_AAvg	If the condition of the home is Above Average (es = 1, o = 0)	2,042	0.27	0.45	1,445	0.29	0.46
Cnd_High	If the condition of the home is High (es = 1, o = 0)	440	0.06	0.24	7	0.07	0.25
Vista_Poor	If the Scenic ista from the home is Poor (es = 1, o = 0)	470	0.06	0.24	10	0.06	0.24
Vista_BAvg	If the Scenic ista from the home is Below Average (es = 1, o = 0)	4, 01	0.58	0.49	2,857	0.58	0.49
Vista_Avg	If the Scenic ista from the home is Average (es = 1, o = 0)	1,912	0.26	0.44	1,247	0.25	0.44
Vista_AAvg	If the Scenic ista from the home is Above Average (es = 1, o = 0)	659	0.09	0.28	448	0.09	0.29
Vista_Prem	If the Scenic ista from the home is Premium (es = 1, o = 0)	117	0.02	0.12	75	0.02	0.12
SaleYear	The year the home was sold	7,459	2002	2.9	4,9 7	2004	2.

"Freq." applies to the number of cases the parameter's value is not zero

Table 7: Summary of Variables of Interest: All Sales and Post-Construction Sales

		All Sales			Post Construction Sales		
Variable Name	**Description**	**Freq. ***	**Mean**	**Std. Dev.**	**Freq. ***	**Mean**	**Std. Dev.**
View_None	If the home sold after construction began and had no view of the turbines (es = 1, o = 0)	4,207	0.56	0.50	4,207	0.85	0. 6
View_Minor	If the home sold after construction began and had a Minor iew of the turbines (es = 1, o = 0)	561	0.08	0.26	561	0.11	0. 2
View_Mod	If the home sold after construction began and had a Moderate iew of the turbines (es = 1, o = 0)	106	0.01	0.12	106	0.02	0.15
View_Sub	If the home sold after construction began and had a Substantial iew of the turbines (es = 1, o = 0)	5	-	0.07	5	0.01	0.08
View_Extrm	If the home sold after construction began and had a Extreme iew of the turbines (es = 1, o = 0)	28	-	0.06	28	0.01	0.08
DISTANCE †	istance to nearest turbine if the home sold after facility announcement , otherwise 0	5,705	2.5	2.59	4,895	.57	1.68
Mile_Less_0.57 †	If the home sold after facility announcement and was within 0.57 miles (000 feet) of the turbines (es = 1, o = 0)	80	0.01	0.09	67	0.01	0.12
Mile_0.57to1 †	If the home sold after facility announcement and was between 0.57 miles (000 feet) and 1 mile of the turbines (es = 1, o = 0)	65	0.01	0.09	58	0.01	0.11
Mile_1to3 †	If the home sold after facility announcement and was between 1 and miles of the turbines (es = 1, o = 0)	2, 59	0.27	0.44	2,019	0.41	0.49
Mile_3to5 †	If the home sold after facility announcement and was between and 5 miles of the turbines (es = 1, o = 0)	2,200	0.26	0.44	1,92	0. 9	0.49
Mile_Gtr5 †	If the home sold after facility announcement and was outside 5 miles of the turbines (es = 1, o = 0)	1,000	0.12	0. 2	870	0.18	0. 8

"Freq." applies to the number of cases the parameter's value is not zero

"All Sales" freq., mean and standard deviation DISTANCE and DISTANCE fixed effects variables (e.g., Mile_1to3) include transactions that occurred after facility "announcement" and before "construction" as well as those that occured post-construction

4. Base Hedonic Model

This section uses the primary hedonic model (Base Model) to assess whether residential sales prices are affected, in a statistically measurable way, by views of and proximity to wind power facilities. In so doing, it simultaneously tests for the presence of the three potential property value stigmas associated with wind power facilities: Area, Scenic ista, and uisance. This section begins with a discussion of the dataset that is used and the form of the model that is estimated, and then turns to the results of the analysis. arious alternative hedonic models are discussed and estimated in Section 5, with Sections 6 and 7 providing a discussion of and results from the repeat sales and sales volume models.

4.1. Dataset

The data used for the Base Model were described in Section . . A key threshold question is whether or not to include the residential transactions that pre-date the relevant wind facility. Specifically, though the complete dataset consists of 7,459 residential transactions, a number of these transactions (n = 2,522) occurred before the wind facility was constructed. Should these homes which, at the time of sale, would not have had any view of or distance to the wind facility, be included Two approaches could be applied to address this issue. First, pre-construction transactions could be included in the hedonic model either as part of the reference category within which no wind-project property value impacts are assumed to exist, or instead by specifically identifying these pre-construction transactions through an indicator variable. Second, and alternatively, pre-construction transactions could simply be excluded from the analysis altogether.

For the purpose of the Base Model, the latter approach is used, therefore relying on only the post-construction subset of 4,9 7 residential transactions. This approach, as compared to the others, results in somewhat more intuitive findings because all homes have a distance greater than zero and have a possibility of some view of the turbines. More importantly, this approach minimizes the chance of inaccuracies that may otherwise exist due to inflation adjustment concerns or outdated home characteristics information.[50] onetheless, to test for the implications of this choice of datasets, alternative hedonic models that use the full dataset were estimated, and are discussed in detail in Sections 5. and 5.4.

[50] Home characteristics were obtained as of the last property assessment. The timing of that assessment relative to the timing of the home sale transaction dictates how representative the assessed home characteristics are of the subject home when it was sold. For example, if a home sold early in the study period but subsequently had significant improvements made that are reflected in the current assessment data used in the analysis, the model would assign value to these home characteristics at the time of sale when, in fact, those characteristics were inaccurate. Additionally, the inflation adjustment index used in this analysis to translate home values to real 1996 dollars came from the nearest or more appropriate municipal statistical area (MSA). Many of the wind projects in the analysis are located in relatively rural parts of the country, and the housing market in the nearest metropolitan area could be different than the market surrounding wind projects. Although these areas have – in many instances – recently begun to attract home buyers willing to commute back to the metropolitan areas on which the index is based, the older index adjustments are likely less accurate than the more recent adjustments. Using a subset of the data for the majority of the analyses that removes the older, pre-construction, homes minimizes both of these biases.

4.2. Model Form

A standard semi-log functional form is used for the hedonic models (as was discussed in Section 2.1), where the dependent variable (sales price in inflation-adjusted 1996 dollars) is transformed to its natural log form and the independent variables (e.g., square feet and acres) are not transformed. Using this form to examine the effect that views of, and distance to, wind facilities have on sales prices, the following basic model is estimated:

$$\ln(\mathrm{P}) = \beta_0 + \beta_1 \quad + \sum_{\mathrm{s}} \beta_2 \mathrm{S} + \sum_{\mathrm{k}} \beta \quad + \sum_{\mathrm{v}} \beta_4 \quad \mathrm{IEW} + \sum_{\mathrm{d}} \beta_5 \quad \mathrm{ISTA} \quad \mathrm{CE} + \varepsilon \tag{1}$$

where

P represents the inflation-adjusted sales price,

is the spatially weighted neighbors predicted sales price,

S is the vector of *s* Study Area fixed effects variables (e.g., WA , KCC, etc.),

is a vector of *k* home and site characteristics (e.g., acres, square feet, number of bathrooms, condition of the home, age of home, ISTA, etc.),

IEW is a vector of *v* categorical view of turbine variables (e.g., MI , M E ATE, etc.),

ISTA CE is a vector of *d* categorical distance to turbine variables (e.g., less than 000 feet, between one and three miles, etc.),

β_0 is the constant or intercept across the full sample,

β_1 is a parameter estimate for the spatially weighted neighbor s predicted sales price,

β_2 is a vector of *s* parameter estimates for the study area fixed effects as compared to homes sold in the Washington/ regon (WA) study area,

β_3 is a vector of *k* parameter estimates for the home and site characteristics,

β_4 is a vector of *v* parameter estimates for the IEW variables as compared to homes sold with no view of the turbines,

β_5 is a vector of *d* parameter estimates for the ISTA CE variables as compared to homes sold situated outside of five miles, and

ε is a random disturbance term.

As such, this model, and all subsequent hedonic models, has four primary groups of parameters: variables of interest, spatial adjustments, study-area fixed effects, and home and site characteristics.

The variables of interest, IEW and ISTA CE, are the focus of this study, and allow the investigation of the presence of Area, Scenic ista, and uisance Stigmas. These variables were defined in Section , and are summarized in Table 8. Both IEW and ISTA CE appear in the model together because a home s value may be affected in part by the magnitude of the view of the wind turbines, and in part by the distance from the home to those turbines, and both variables appear in the Base Model as ordered categorical values. The coefficients associated with these two vectors of variables (β_4 and β_5) represent the marginal impact of views of, and distances to, wind turbines on sales prices, as compared to a reference category of residential transactions, and should be ordered monotonically from low to high.[51] This form of variable was used to

[51] eference category refers to the subset of the sample to which other observations are compared, and is pertinent when using categorical or fixed effect variables.

impose the least structure on the underlying data.[52] For the purpose of the Base Model, the reference category for the ISTA CE variables are those transactions of homes that were situated outside of five miles from the nearest wind turbine. The reference category for the IEW variables are those transactions of homes that did not have a view of the wind facility upon sale. Among the post-construction sample of homes, these reference homes are considered the least likely to be affected by the presence of the wind facilities.[5]

Table 8: List of Variables of Interest Included in the Base Model

Variable Name	Description	Type	Expected Sign
View_None	If the home sold after construction began and had no view of the turbines (es = 1, o = 0)	eference	n/a
View_Minor	If the home sold after construction began and had a Minor iew of the turbines (es = 1, o = 0)	C	-
View_Mod	If the home sold after construction began and had a Moderate iew of the turbines (es = 1, o = 0)	C	-
View_Sub	If the home sold after construction began and had a Substantial iew of the turbines (es = 1, o = 0)	C	-
View_Extrm	If the home sold after construction began and had an Extreme iew of the turbines (es = 1, o = 0)	C	-
Mile_Less_0.57	If the home sold after facility construction and was within 0.57 miles (000 feet) of the turbines (es = 1, o = 0)	C	-
Mile_0.57to1	If the home sold after facility construction and was between 0.57 miles (000 feet) and 1 mile of the turbines (es = 1, o = 0)	C	-
Mile_1to3	If the home sold after facility construction and was between 1 and miles of the turbines (es = 1, o = 0)	C	-
Mile_3to5	If the home sold after facility construction and was between and 5 miles of the turbines (es = 1, o = 0)	C	-
Mile_Gtr5	If the home sold after facility construction and was outside 5 miles of the turbines (es = 1, o = 0)	eference	n/a

"OC" Ordered Categorical (1 = yes, 0 = no) values are interpreted in relation to the reference categorical case and are expected to have a monotonic order from low to high.

The three stigmas are investigated though these IEW and ISTA CE variables. Scenic ista Stigma is investigated through the IEW variables. Area and uisance Stigmas, on the other hand, are investigated through the ISTA CE variables. To distinguish between Area and

[52] In place of the ordered categorical ISTA CE variables, practitioners often rely on a continuous ISTA CE form (e.g., Sims et al., 2008). Similar to ordered categorical variables, continuous variables have a natural ordering, either ascending or descending, but, unlike categorical variables, these continuous values are on a scale. Therefore, given any two of its values $_1$ and $_2$ and a specific functional form, the ratio $_1/_2$ and the distance $_1 - _2$ have a fixed meaning. Examples of continuous variables other than ISTA CE that are commonly used include the number of square feet of living area (in 1000s) in a home (S FT 1000) or the acres in the parcel (AC ES). A continuous functional form of this nature imposes structure because practitioners must decide how price is related to the underlying variables through the selection of a specific functional relationship between the two. For instance, in the case of ISTA CE, is there a linear relationship (which would imply a similar marginal difference between two distances both near and far from the turbines), does it decay slowly as distance grows, or does it fade completely at some fixed distance Because of the lack of literature in this area, no *a priori* expectations for which functional form is the best were established, and therefore unstructured categorical variables are used in the Base Model. onetheless, a continuous ISTA CE form is explored in Section 5.2.

[5] It is worth noting that these reference homes are situated in both rural and urban locales and therefore are not uniquely affected by influences from either setting. This further reinforces their worthiness as a reference category.

uisance Stigma, it is assumed that uisance effects are concentrated within one mile of the nearest wind turbine, while Area effects will be considered for those transactions outside of one mile. Any property value effects discovered outside of one mile and based on the ISTA CE variables are therefore assumed to indicate the presence of Area Stigma, while impacts within a mile may reflect the combination of uisance and Area Stigma.

The second set of variables in the Base Model - spatial adjustments - correct for the assumed presence of spatial autocorrelation in the error term (ε). It is well known that the sales price of a home can be systematically influenced by the sales prices of those homes that have sold nearby. Both the seller and the buyer use information from comparable surrounding sales to inform them of the appropriate transaction price, and nearby homes often experience similar amenities and disamenities. This lack of independence of home sale prices could bias hedonic regression results and, to help correct for this bias, a spatially (i.e., distance) weighted neighbors sales price ( ) is included in the model. Empirically, the neighbors price has been found to be a strong (and sometimes even the strongest) predictor of home values (Leonard and Murdoch, forthcoming), and the coefficient β_1 is expected to be positive, indicating a positive correlation between the neighbors and subject home s sales price. A more-detailed discussion of the importance of this variable, and how it was created, is contained in Appendix .

The third group of variables in the Base Model - study area fixed effects - control for study area influences and the differences between them. The vector s parameters β_2 represent the marginal impact of being in any one of the study areas, as compared to a reference category. In this case, the reference category is the Washington/ regon (WA) study area.[54] The estimated coefficients for this group of variables represent the combined effects of school districts, tax rates, crime, and other locational influences across an entire study area. Although this approach greatly simplifies the estimation of the model, because of the myriad of influences captured by these study-area fixed effects variables, interpreting the coefficient can be difficult. In general, though, the coefficients simply represent the mean difference in sales prices between the study areas and the reference study area (WA). These coefficients are expected to be strongly influential, indicating significant differences in sales prices across study areas.

The fourth group of variables in the Base Model are the core home and site characteristics ( ), and include a range of continuous (C),[55] discrete ( ),[56] binary (B),[57] and ordered categorical (C) variables. The specific home and site variables included in the Base Model are listed in Table 9 along with the direction of expected influence.[58] ariables included are age

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[54] Because there is no intent to focus on the coefficients of the study area fixed effect variables, the reference case is arbitrary. Further, the results for the other variables in the model are completely independent of this choice.

[55] See discussion in footnote 52 on previous page.

[56] iscrete variables, similar to continuous variables, are ordered and the distance between the values, such as $_1$ and $_2$, have meaning, but for these variables, there are only a relatively small number of discrete values that the variable can take, for example, the number of bathrooms in a home (BATH MS).

[57] Binary variables have only two conditions: on or off (i.e., 1 or 0 respectively). Examples are whether the home has central air conditioning (CE T AL AC) or if the home is situated on a cul-de-sac (CUL E SAC). The coefficients for these variables are interpreted in relation to when the condition is off.

[58] For those variables with a sign it is expected that as the variable increases in value (or is valued at 1 as would be the case for fixed effects variables) the price of the home will increase, and the converse is true for the variables with a - sign. The expected signs of the variables all follow conventional wisdom (as discussed in

of the home, home and lot size, number of bathrooms and fireplaces, the condition of the home, the quality of the scenic vista from the home, if the home has central AC, a stone exterior, and/or a finished basement, and whether the home is located in a cul-de-sac and/or on a water way.[59]

Table 9: List of Home and Site Characteristics Included in the Base Model

Variable Name	Description	Type	Expected Sign
AgeatSale	The age of the home at the time of sale in years	C	-
AgeatSale_Sqrd	The age of the home at the time of sale squared	C	+
Sqft_1000	The number of square feet of above grade finished living area (in 1000s)	C	+
Acres	The number of Acres sold with the residence	C	+
Baths	The number of Bathrooms (Full Bath = 1, Half Bath = 0.5)		+
ExtWalls_Stone	If the home has exterior walls of stone, brick or stucco (es = 1, o = 0)	B	+
CentralAC	If the home has a Central AC unit (es = 1, o = 0)	B	+
Fireplace	The number of fireplace openings		+
Cul_De_Sac	If the home is situated on a cul-de-sac (es = 1, o = 0)	B	+
FinBsmt	If finished basement sqft 50 times first floor sqft (es = 1, o = 0)	B	+
Water_Front	If the home shares a property line with a body of water or river (es = 1, o = 0)	B	+
Cnd_Low	If the condition of the home is Poor (es = 1, o = 0)	C	-
Cnd_BAvg	If the condition of the home is Below Average (es = 1, o = 0)	C	-
Cnd_Avg	If the condition of the home is Average (es = 1, o = 0)	eference	n/a
Cnd_AAvg	If the condition of the home is Above Average (es = 1, o = 0)	C	+
Cnd_High	If the condition of the home is High (es = 1, o = 0)	C	+
Vista_Poor	If the Scenic ista from the home is Poor (es = 1, o = 0)	C	-
Vista_BAvg	If the Scenic ista from the home is Below Average (es = 1, o = 0)	C	-
Vista_Avg	If the Scenic ista from the home is Average (es = 1, o = 0)	eference	n/a
Vista_AAvg	If the Scenic ista from the home is Above Average (es = 1, o = 0)	C	+
Vista_Prem	If the Scenic ista from the home is Premium (es = 1, o = 0)	C	+

"C" Continuous, "D" Discrete, and "B" Binary (1 = yes, 0 = no) values are interpreted in relation to "No"

"OC" Ordered Categorical (1 = yes, 0 = no) values are interpreted in relation to the reference categorical case and are expected to have a monotonic order from low to high.

Sirmans et al., 2005a), save AgeatSale and AgeatSale Sqrd, which are expected to be negative and positive, respectively. The magnitude of the coefficient of AgeatSale is expected to be larger than that of AgeatSale Sqrd indicating an initial drop in value as a home increases in age, and then an increase in value as the home becomes considerably older and more historic.

[59] Some characteristics, such as whether the home had a deck, a pool, or is located on a public sewer, are not available consistently across the dataset and therefore are not incorporated into the model. ther characteristics, such as the number of bedrooms, the number of stories, or if the home had a garage, are available but are omitted from the final model because they are highly correlated with characteristics already included in the model and therefore do not add significantly to the model s explanatory power. More importantly, and as discussed in Appendix , when their inclusion or exclusion are tested, the results are stable with those derived from the Base Model.

It should be emphasized that in the Base Hedonic Model - equation (1) - and in all subsequent models presented in Section 5, all variables of interest, spatial adjustments, and home and site characteristics are pooled, and therefore their estimates represent the average across all study areas. Ideally, one would have enough data to estimate a model at the study area level - a fully unrestricted model - rather than pooled across all areas. This fully unrestricted model form, along with 15 other model forms (with some variables restricted and others not), are discussed in detail in Appendix F. In total, these 16 different models were estimated to explore which model was the most parsimonious (had the fewest parameters), performed the best (e.g., had the highest adjusted ^{2} and the lowest Schwarz information criterion[60]), and had the most stable coefficients and standard errors. The basic pooled model described by equation (1) is found to fit that description, and that model is therefore chosen as the Base Model to which others are compared. By making this choice the effort concentrates on identifying the presence of potential property value impacts across all of the study areas in the sample as opposed to any single study area.[61]

Finally, to assure that the model produces the best linear unbiased parameter estimates, the underlying assumptions of rdinary Least Squares (LS) regression techniques must be verified:

1) Homoskedastic error term;
2) Absence of temporal serial correlation;
) easonably limited multicollinearity; and
4) Appropriate controls for outliers and influencers.[62]

These assumptions, and the specific approaches that are used to address them, are discussed in detail in Appendix .

4.3. Analysis of Results

Table 10 (on page 2)presents the results of the Base Model (equation 1).[6] The model performs well, with an adjusted ^{2} of 0.77.[64] The spatial adjustment coefficient (β_1) of 0.29 (*p* value 0.00) indicates that a 10 increase in the spatially weighted neighbor s price increases the subject home s value by an average of 2.9 . The study-area fixed effects (β_2) variables are all significant at the one percent level, demonstrating important differences in home valuations

[60] The Schwarz information criterion measures relative parsimony between similar models (Schwarz, 1978).

[61] Because effects might vary between study areas, and the models estimate an average across all study areas, the full range of effects in individual study areas will go undetermined. That notwithstanding, there is no reason to suspect that effects will be completely washed out. For that to occur, an effect in one study area would have to be positive while in another area it would have to be negative, and there is no reason to suspect that sales prices would increase because of the turbines in one community while decreasing in other communities.

[62] The absence of spatial autocorrelation is often included in the group of assumptions, but because it was discussed above (and in Appendix), and is addressed directly by the variable ($_i$) included in the model, it is not included in this list.

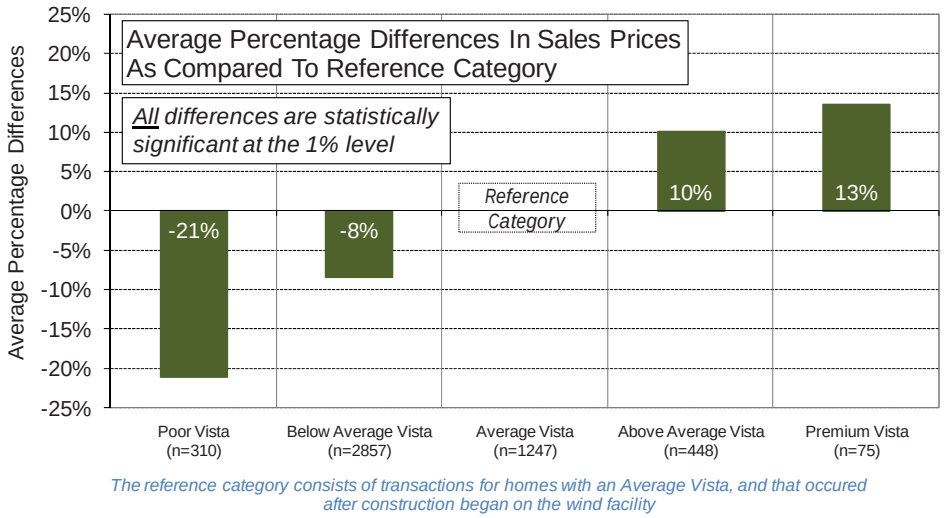
[6] This model and all subsequent models were estimated using the P C E procedure of SAS ersion 9.2 TS1M0, which produces White s corrected standard errors.

[64] The appropriateness of the ^{2} of 0.77 for this research is validated by the extensive hedonic literature that precedes it (see e.g., Kroll and Priestley, 1992; Boyle and Kiel, 2001; Simons, 2006b).

between the reference study area (WA) and the other nine study areas.[65] The sign and magnitudes of the home and site characteristics are all appropriate given the *a priori* expectations, and all are statistically significant at the one percent level.[66]

f particular interest are the coefficient estimates for scenic vista (ISTA) as shown in Figure 5. Homes with a P vista rating are found, on average, to sell for 21 less (*p* value 0.00) than homes with an A E A E rating, while BEL W A E A E homes sell for 8 less (*p* value 0.00). Conversely, homes with an AB E A E A E vista are found to sell for 10 more (*p* value 0.00) than homes with an A E A E vista, while P EMIUM vista homes sell for 1 more than A E A E homes (*p* value 0.00). Based on these results, it is evident that home buyers and sellers capitalize the quality of the scenic vista in sales prices.[67]

Figure 5: Results from the Base Model for VISTA



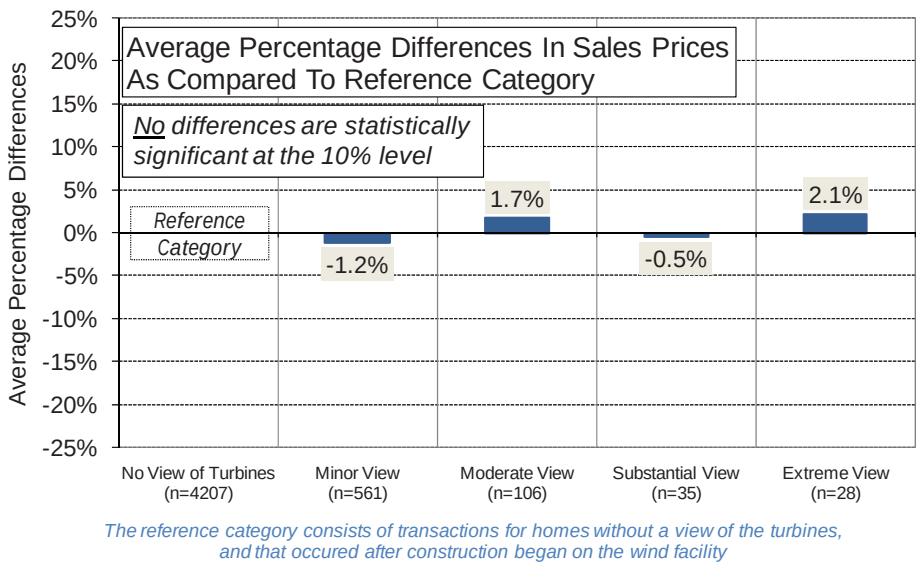
[65] The reference category WA study area has the highest mean and median house values in the sample (as shown in Appendix A) so the negative coefficients for all the study area fixed effect variables are appropriate.

[66] To benchmark the results against those of other practitioners the research by Sirmans et al. (2005a; 2005b) was consulted. They conducted a meta-analysis of 64 hedonic studies carried out in multiple locations in the U.S. during multiple time periods, and investigated the coefficients of ten commonly used characteristics, seven of which were included in the model. The similarities between their mean coefficients (i.e., the average across all 64 studies) and those estimated in the present Base Model are striking. The analysis presented here estimates the effect of square feet (in 1000s) on log of sales price at 0.28 and Sirmans et al. provide an estimate of 0. 4, while AC ES was similarly estimated (0.02 to 0.0 , Base Model and Sirmans et al., respectively). Further, A EATSALE (age at the time of sale) (-0.006 to -0.009), BATH MS (0.09 to 0.09), CE T ALAC (0.09 to 0.08), and FI EPLACE (0.11 to 0.09) all similarly compare. As a group, the Base Model estimates differ from Sirmans et al. estimates in all cases by no more than a third of the Sirmans et al. mean estimate s standard deviation. This, taken with the relatively high adjusted ^{2} of the Base Model, demonstrates the appropriateness of the model s specification.

[67] To benchmark these results they are compared to the few studies that have investigated the contribution of inland scenic vistas to sales prices. Benson et al. (2000) find that a mountain vista increases sales price by 8 , while Bourassa et al. (2004) find that wide inland vistas increase sales price by 7.6 . These both compare favorably to the 10 and 14 above average and premium rated ISTA estimates. Comparable studies for below average and poor ISTA were not found and therefore no benchmarking of those coefficients is conducted. Finally, it should again be noted that a home s scenic vista, as discussed in Section .2. , was ranked without taking the presence of the wind turbines into consideration, even if those turbines were visible at the time of home sale.

espite this finding for scenic vista, however, no statistically significant relationship is found between views of wind turbines and sales prices.[68] The coefficients for the IEW parameters (β_4) are all relatively small, none are statistically significant, and they are not monotonically ordered (see Figure 6). Homes with E T EME or SUBSTA TIAL view ratings, for which the Base Model is expected to find the largest differences, sell for, on average, 2.1 more (*p* value 0.80) and 0.5 less (*p* value 0.94) than IEW homes that sold in the same post-construction period. Similarly, homes with M E ATE or MI view ratings sell, on average, for 1.7 more (*p* value 0.58) and 1.2 less (*p* value 0.40) than IEW homes, respectively. one of these coefficients are sizable, and none are statistically different from zero. These results indicate that, among this sample at least, a statistically significant relationship between views of wind turbines and residential property values is not evident. In other words, there is an absence of evidence of a Scenic ista Stigma in the Base Model.

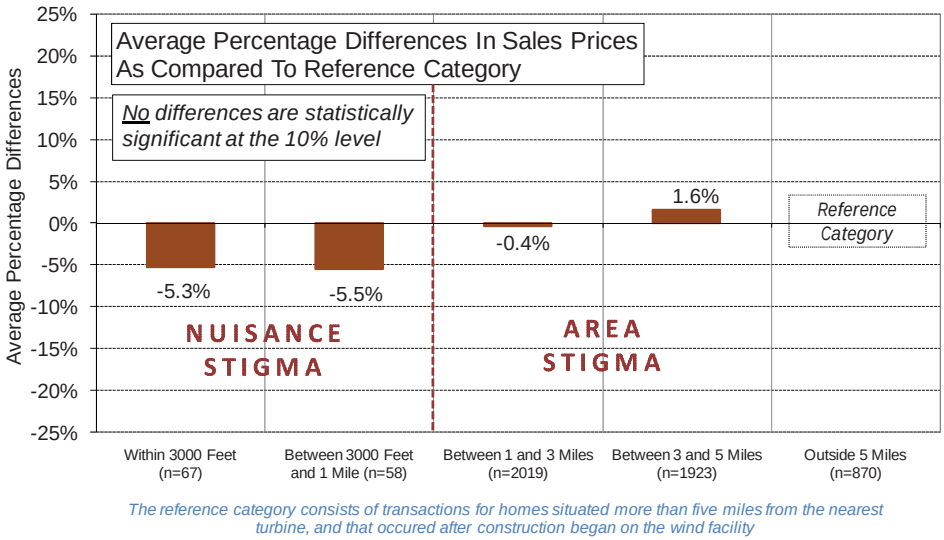
Figure 6: Results from the Base Model for VIEW



The coefficients for the ISTA CE parameters (β_5) are also all relatively small and none are statistically significant (see Figure 7). Homes that are situated within 000 feet (0.57 miles) of the nearest wind turbine, at the time of sale, are found to sell for 5. less (*p* value 0.40), on average, than homes outside of 5 miles that sold in the same post-construction period. Meanwhile, homes between 000 feet and 1 mile sold for 5.5 less (*p* value 0. 0), on average, than homes more than 5 miles away. Homes that are within 1 to miles of the nearest turbine, as compared to homes outside of 5 miles, sold for essentially the same, on average (coefficient = 0.004, *p* value 0.80), while homes between and 5 miles sold for 1.6 more (*p* value 0.2).

[68] A significance level of 10 is used throughout this report, which corresponds to a *p*-value at or above 0.10. Although this is more liberal than the often used 5 (*p*-value at or above 0.05), it was chosen to give more opportunities for effects that might be fairly weak to be considered significant.

Figure 7: Results from the Base Model for DISTANCE



Looking at these results as a whole, a somewhat monotonic order from low to high is found as homes are situated further away from wind facilities, but all of the coefficients are relatively small and none are statistically different from zero. This suggests that, for homes in the sample at least, there is a lack of statistical evidence that the distance from a home to the nearest wind turbine impacts sales prices, and this is true regardless of the distance band.[69] As such, an absence of evidence of an Area or uisance Stigma is found in the Base Model. That notwithstanding, the -5 coefficients for homes that sold within one mile of the nearest wind turbine require further scrutiny. Even though the differences are not found to be statistically significant, they might point to effects that exist but are too small for the model to deem statistically significant due to the relatively small number of homes in the sample within 1 mile of the nearest turbine. Alternatively, these homes may simply have been devalued even before the wind facility was erected, and that devaluation may have carried over into the post construction period (the period investigated by the Base Model). To explore these possibilities, transactions that occurred well before the announcement of the wind facility to well after construction are investigated in the Temporal Aspects Model in the following Alternative Models section.

[69] It is worth noting that the number of cases in each of these categories (e.g., n = 67 for homes inside of 000 feet and n = 58 between 000 feet and one mile) are small, but are similar to the numbers of cases for other variables in the same model (e.g., L W C ITI , n = 69; P EMIUM ISTA, n = 75), the estimates of which were found to be significant above the 1 level.

Table 10: Results from the Base Model

	Coef.	SE	p Value	*n*
Intercept	7.62	0.18	0.00	
Nbr_LN_SalePrice96_hat	0.29	0.02	0.00	4,9 7
AgeatSale	-0.006	0.0004	0.00	4,9 7
AgeatSale_Sqrd	0.00002	0.00000	0.00	4,9 7
Sqft_1000	0.28	0.01	0.00	4,9 7
Acres	0.02	0.00	0.00	4,9 7
Baths	0.09	0.01	0.00	4,9 7
ExtWalls_Stone	0.21	0.02	0.00	1,486
CentralAC	0.09	0.01	0.00	2,575
Fireplace	0.11	0.01	0.00	1,8 4
FinBsmt	0.08	0.02	0.00	67
Cul_De_Sac	0.10	0.01	0.00	992
Water_Front	0.	0.04	0.00	87
Cnd_Low	-0.45	0.05	0.00	69
Cnd_BAvg	-0.24	0.02	0.00	50
Cnd_Avg	mitted	mitted	mitted	2,727
Cnd_AAvg	0.14	0.01	0.00	1,445
Cnd_High	0.2	0.02	0.00	7
Vista_Poor	-0.21	0.02	0.00	10
Vista_BAvg	-0.08	0.01	0.00	2,857
Vista_Avg	mitted	mitted	mitted	1,247
Vista_AAvg	0.10	0.02	0.00	448
Vista_Prem	0.1	0.04	0.00	75
WAOR	mitted	mitted	mitted	519
TXHC	-0.75	0.0	0.00	1,071
OKCC	-0.44	0.02	0.00	476
IABV	-0.24	0.02	0.00	605
ILLC	-0.09	0.0	0.00	21
WIKCDC	-0.14	0.02	0.00	725
PASC	-0. 1	0.0	0.00	291
PAWC	-0.07	0.0	0.01	222
NYMCOC	-0.20	0.0	0.00	46
NYMC	-0.15	0.02	0.00	469
Post_Con_NoView	mitted	mitted	mitted	4,207
View_Minor	-0.01	0.01	0.40	561
View_Mod	0.02	0.0	0.58	106
View_Sub	-0.01	0.07	0.94	5
View_Extrm	0.02	0.09	0.80	28
Mile_Less_0_57	-0.05	0.06	0.40	67
Mile_0_57to1	-0.05	0.05	0. 0	58
Mile_1to3	0.00	0.02	0.80	2,019
Mile_3to5	0.02	0.01	0.2	1,92
Mile_Gtr5	mitted	mitted	mitted	870

"Omitted" = reference category for fixed effects variables
"n" indicates number of cases in category when category = "1"

Model Information

Model Equation Number	**1**
Dependent Variable	**LN_SalePrice96**
Number of Cases	**4937**
Number of Predictors (k)	**37**
F Statistic	**442.8**
Adjusted R Squared	**0.77**

5. Alternative Hedonic Models

The Base Hedonic Model presented in Section 4 found that residential property values have, on average, not been measurably affected by the presence of nearby wind facilities. To test the robustness of this result and to test for other possible impacts from nearby wind projects, the report now turns to a number of other hedonic models. These Alternative Models were created to investigate different approaches to exploring the impact of the variables of interest (1 and 2, below) and to assess the presence of impacts that are not otherwise fully captured by the Base Model (through 6, below).

1) **View and Distance Stability Models:** Using only post-construction transactions (the same as the Base Model) these models investigate whether the Scenic ista Stigma (as measured with IEW) results are independent of the uisance and Area Stigma results (as measured by ISTA CE) and vice versa.[70]
2) **Continuous Distance Model:** Using only post-construction transactions, this model investigates Area and uisance Stigmas by applying a continuous distance parameter as opposed to the categorical variables for distance used in the previous models.
) **All Sales Model:** Using all transactions, this model investigates whether the results for the three stigmas change if transactions that occurred before the announcement and construction of the wind facility are included in the sample.
4) **Temporal Aspects Model:** Using all transactions, this model further investigates Area and uisance Stigmas and how they change for homes that sold more than two years pre-announcement through the period more than four years post-construction.
5) **Home Orientation Model:** Using only post-construction transactions, this model investigates the degree to which a home s orientation to the view of wind turbines affects sales prices.
6) **View and Vista Overlap Model:** Using only post-construction transactions, this model investigates the degree to which the overlap between the view of a wind facility and a home s primary scenic vista affects sales prices.

Each of these models is described in more depth in the pages that follow. esults are shown for the variables of interest only; full results are contained in Appendix H.

5.1. View and Distance Stability Models

The Base Model (equation 1) presented in Section 4 includes both ISTA CE and IEW variables because a home s value might be affected in part by the magnitude of the view of a nearby wind facility and in part by the distance from the home to that facility. These two variables may be related, however, in-so-far as homes that are located closer to a wind facility are likely to have a more-dominating view of that facility. To explore the degree to which these two sets of variables are independent of each other (i.e. not collinear) and to further test the robustness of the Base Model results two alternative hedonic models are run, each of which includes only one of the sets of parameters (ISTA CE or IEW). Coefficients from these models are then compared to the Base Model results.

[70] ecall that the qualitative IEW variable incorporated the visible distance to the nearest wind facility.

5.1.1. Dataset and Model Form

The same dataset is used as in the Base Model, focusing again on post-construction transactions (n = 4,9 7). To investigate ISTA CE effects alone the following model is estimated:

$$\ln(\mathrm{P}) = \beta_0 + \beta_1 \quad + \sum_{\mathrm{s}} \beta_2 \mathrm{S} + \sum_{\mathrm{k}} \beta \quad + \sum_{\mathrm{d}} \beta_5 \quad \mathrm{ISTA} \quad \mathrm{CE} + \varepsilon \tag{2}$$

where

P represents the inflation-adjusted sales price,

is the spatially weighted neighbors predicted sales price,

S is the vector of *s* Study Area fixed effects variables (e.g., WA , KCC, etc.),

is a vector of *k* home and site characteristics (e.g., acres, square feet, number of bathrooms, condition of the home, age of home, ISTA, etc.),

ISTA CE is a vector of *d* categorical distance variables (e.g., less than 000 feet, between one and three miles, etc.),

β_0 is the constant or intercept across the full sample,

β_1 is a parameter estimate for the spatially weighted neighbor s predicted sales price,

β_2 is a vector of *s* parameter estimates for the study area fixed effects as compared to transactions of homes in the WA study area,

β_3 is a vector of *k* parameter estimates for the home and site characteristics,

β_5 is a vector of *d* parameter estimates for the ISTA CE variables as compared to transactions of homes situated outside of five miles, and

ε is a random disturbance term.

The parameters of primary interest are β_5, which represent the marginal differences between home values at various distances from the wind turbines as compared to the reference category of homes outside of five miles. These coefficients can then be compared to the same coefficients estimated from the Base Model.

Alternatively, to investigate the IEW effects alone, the following model is estimated:

$$\ln(\mathrm{P}) = \beta_0 + \beta_1 \quad + \sum_{\mathrm{s}} \beta_2 \mathrm{S} + \sum_{\mathrm{k}} \beta \quad + \sum_{\mathrm{v}} \beta_4 \quad \mathrm{IEW} + \varepsilon \tag{ }$$

where

IEW is a vector of *v* categorical view variables (e.g., MI , M E ATE, etc.),

β_4 is a vector of *v* parameter estimates for the IEW variables, and

all other components are as defined in equation (2).

The parameters of primary interest in this model are β_4, which represent the marginal differences between home values for homes with varying views of wind turbines at the time of sale as compared to the reference category of homes without a view of those turbines. Again, these coefficients can then be compared to the same coefficients estimated from the Base Model.

ur expectation for both of the models described here is that the results will not be dramatically different from the Base Model, given the distribution of IEW values across the ISTA CE values, and vice versa, as shown in Table 11. Except for E T EME view, which is

concentrated inside of 000 feet, all view ratings are adequately distributed among the distance categories.

Table 11: Frequency Crosstab of VIEW and DISTANCE Parameters

	Inside 3000 Feet	Between 3000 Feet and 1 Mile	Between 1 and 3 Miles	Between 3 and 5 Miles	Outside 5 Miles	Total
No View	6	12	165	1695	841	**4207**
Minor View	14	24	294	202	27	**561**
Moderate View	8	1	62	21	2	**106**
Substantial View	11	9	10	5	0	**35**
Extreme View	28	0	0	0	0	**28**
TOTAL	**67**	**58**	**2019**	**1923**	**870**	**4937**

5.1.2. Analysis of Results

Summarized results for the variables of interest from the Base Model and the two Alternative Stability Models are presented in Table 12. (For brevity, the full set of results for the models is not shown in Table 12, but is instead included in Appendix H.) The adjusted ^{2} for the iew and istance Stability Models is the same as for the Base Model, 0.77. All study area, spatial adjustment, and home and site characteristics are significant at or above the one percent level and are similar in magnitude to the estimates presented earlier for the Base Model.

The ISTA CE and IEW coefficients, β_5 and β_4, are stable, changing no more than , with most (7 out of 8) not experiencing a change greater than 1 . In all cases, changes to coefficient estimates for the variables of interest are considerably less than the standard errors. Based on these results, there is confidence that the correlation between the IEW and ISTA CE variables is not responsible for the findings and that these two variables are adequately independent to be included in the same hedonic model regression. As importantly, no evidence of Area, Scenic ista, or uisance Stigma is found in the sample, as none of the IEW or ISTA CE variables are found to be statistically different from zero.

Table 12: Results from Distance and View Stability Models

		Base Model			Distance Stability			View Stability		
Variables of Interest	***n***	**Coef**	**SE**	**p Value**	**Coef**	**SE**	**p Value**	**Coef**	**SE**	**p Value**
No View	4207	mitted	mitted	mitted				mitted	mitted	mitted
Minor View	561	-0.01	0.01	0. 9				-0.02	0.01	0.24
Moderate View	106	0.02	0.0	0.57				0.00	0.0	0.90
Substantial View	5	-0.01	0.07	0.92				-0.04	0.06	0.45
Extreme View	28	0.02	0.09	0.77				-0.0	0.06	0.58
Inside 3000 Feet	67	-0.05	0.06	0. 1	-0.04	0.04	0.25			
Between 3000 Feet and 1 Mile	58	-0.05	0.05	0.20	-0.06	0.05	0.17			
Between 1 and 3 Miles	2019	0.00	0.02	0.80	-0.01	0.02	0.71			
Between 3 and 5 Miles	192	0.02	0.01	0.26	0.01	0.01	0. 0			
Outside 5 Miles	870	mitted	mitted	mitted	mitted	mitted	mitted			

"Omitted" = reference category for fixed effects variables. "n" indicates number of cases in category when category = "1"

Model Information

Model Equation Number	**1**	**2**	**3**
Dependent Variable	**LN_SalePrice96**	**LN_SalePrice96**	**LN_SalePrice96**
Number of Cases	**4937**	**4937**	**4937**
Number of Predictors (k)	**37**	**33**	**33**
F Statistic	**442.8**	**496.7**	**495.9**
Adjusted R Squared	**0.77**	**0.77**	**0.77**

5.2. Continuous Distance Model

The potential impact of wind facilities on residential property values based on Area and uisance effects was explored with the Base Model by using five ordered categorical ISTA CE variables. This approach was used in order to impose the least restriction on the functional relationship between distance and property values (as discussed in footnote 52 on page 25). The literature on environmental disamenities, however, more commonly uses a continuous distance form (e.g., Sims et al., 2008), which imposes more structure on this relationship. To be consistent with the literature and to test if a more rigid structural relationship might uncover an effect that is not otherwise apparent with the five distance categories used in the Base Model, a hedonic model that relies upon a continuous distance variable is presented here. ne important benefit of this model is that a larger amount of data (e.g., *n* = 4,9 7) is used to estimate the continuous ISTA CE coefficient then was used to estimate any of the individual categorical estimates in the Base Model (e.g., *n* = 67 inside 000 feet, *n* = 2019 between one and three miles). The Continuous istance Model therefore provides an important robustness test to the Base Model results.

5.2.1. Dataset and Model Form

A number of different functional forms can be used for a continuous ISTA CE variable, including linear, inverse, cubic, quadratic, and logarithmic. f the forms that are considered, an inverse function seemed most appropriate.[71] Inverse functions are used when it is assumed that any effect is most pronounced near the disamenity and that those effects fade asymptotically as distance increases. This form has been used previously in the literature (e.g., Leonard et al., 2008) to explore the impact of disamenities on home values, and is calculated as follows:

$$\text{Inv ISTA CE} = 1/\text{ ISTA CE} \tag{4}$$

where
ISTA CE is the distances to the nearest turbine from each home as calculated at the time of sale for homes that sold in the post-construction period.

For the purpose of the Continuous istance Model, the same dataset is used as in the Base Model, focusing again on post-construction transactions (*n* = 4,9 7). Inv ISTA CE has a maximum of 6.67 (corresponding to homes that were 0.15 miles, or roughly 800 feet, from the nearest wind turbine), a minimum of 0.09 (corresponding to a distance of roughly 11 miles), and a mean of 0. 8(corresponding to a distance of 2.6 miles). This function was then introduced into the hedonic model in place of the ISTA CE categorical variables as follows:

$$\ln(\text{P}) = \beta_0 + \beta_1 \quad + \sum_{\text{s}} \beta_2 \text{S} + \sum_{\text{k}} \beta \quad + \sum_{\text{v}} \beta_4 \quad \text{IEW} + \beta_5 \text{Inv ISTA CE} + \varepsilon \tag{5}$$

where
Inv ISTA CE_{i} is the inverse of the distance to the nearest turbine,
β_5 is a parameter estimate for the inverse of the distance to the nearest turbine, and

[71] The other distance functions (e.g., linear, quadratic, cubic logarithmic) were also tested. Additionally, two-part functions with interactions between continuous forms (e.g., linear) and categorical (e.g., less than one mile) were investigated. esults from these models are briefly discussed below in footnote 72.

all other components are as defined in equation (1).

The coefficient of interest in this model is β_5, which, if effects exist, would be expected to be negative, indicating an adverse effect from proximity to the wind turbines.

5.2.2. Analysis of Results

esults for the variables of interest in the Continuous istance Model and the Base Model are shown in Table 1 . (For brevity, the full set of results for the model is not shown in Table 1 , but is instead included in Appendix H.) The model performs well with an adjusted ^{2} of 0.77. All study area, spatial adjustment, and home and site characteristics are significant at the one percent level. The coefficients for IEW are similar to those found in the Base Model, demonstrating stability in results, and none are statistically significant. These results support the previous findings of a lack of evidence of a Scenic ista Stigma.

ur focus variable Inv ISTA CE produces a coefficient (β_5) that is slightly negative at -1 , but that is not statistically different from zero (*p* value 0.41), implying again that there is no statistical evidence of a uisance Stigma effect nor an Area Stigma effect and confirming the results obtained in the Base Model.[72]

Table 13: Results from Continuous Distance Model

	Base Model				Continuous Distance			
Variables of Interest	**Coef**	**SE**	**p Value**	***n***	**Coef**	**SE**	**p Value**	***n***
No View	mitted	mitted	mitted	4,207	mitted	mitted	mitted	4,207
Minor View	-0.01	0.01	0. 9	561	-0.01	0.01	0. 2	561
Moderate View	0.02	0.0	0.57	106	0.01	0.0	0.77	106
Substantial View	-0.01	0.07	0.92	5	-0.02	0.07	0.64	5
Extreme View	0.02	0.09	0.77	28	0.01	0.10	0.85	28
Inside 3000 Feet	-0.05	0.06	0. 1	67				
Between 3000 Feet and 1 Mile	-0.05	0.05	0.20	58				
Between 1 and 3 Miles	0.00	0.02	0.80	2,019				
Between 3 and 5 Miles	0.02	0.01	0.26	1,92				
Outside 5 Miles	mitted	mitted	mitted	870				
InvDISTANCE					-0.01	0.02	0.41	4,9 7

"Omitted" = reference category for fixed effects variables. "n" = number of cases in category when category = "1"

Model Information

Model Equation Number	**1**	**5**
Dependent Variable	**LN_SalePrice96**	**LN_SalePrice96**
Number of Cases	**4937**	**4937**
Number of Predictors (k)	**37**	**34**
F Statistic	**442.8**	**481.3**
Adjusted R Squared	**0.77**	**0.77**

5.3. All Sales Model

The Base Model presented earlier relied on only those transactions that occurred after the construction of the relevant wind facility. This approach, however, leaves open two key questions. First, it is possible that the property values of all of the post-construction homes in the

[72] As mentioned in footnote 71 on page 6, a number of alternative forms of the continuous distance function were also explored, including two-part functions, with no change in the results presented here. In all cases the resulting continuous distance function was not statistically significant.

sample have been affected by the presence of a wind facility, and therefore that the reference homes in the Base Model (i.e., those homes outside of five miles with no view of a wind turbine) are an inappropriate comparison group because they too have been impacted.[7] Using only those homes that sold before the announcement of the wind facility (pre-announcement) as the reference group would, arguably, make for a better comparison because the sales price of those homes are not plausibly impacted by the presence of the wind facility.[74] Second, the Base Model does not consider homes that sold in the post-announcement but pre-construction period, and previous research suggests that property value effects might be very strong during this period, during which an assessment of actual impacts is not possible and buyers and sellers may take a more-protective and conservative stance (Wolsink, 1989). This subsection therefore presents the results of a hedonic model that uses the full set of transactions in the dataset, pre- and post-construction.

5.3.1. Dataset and Model Form

Unlike the Base Model, in this instance the full set of 7,459 residential transactions is included. The following model is then estimated:

$$\ln(\mathrm{P}) = \beta_0 + \beta_1 \quad + \sum_{\mathrm{s}} \beta_2 \mathrm{S} + \sum_{\mathrm{k}} \beta \quad + \sum_{\mathrm{v}} \beta_4 \quad \mathrm{IEW} + \sum_{\mathrm{d}} \beta_5 \quad \mathrm{ISTA} \quad \mathrm{CE} + \varepsilon \tag{6}$$

where

IEW is a vector of *v* categorical view variables (e.g., E, MI , M E ATE, etc.),

ISTA CE is a vector of *d* categorical distance variables (e.g., less than 000 feet, between one and three miles, outside of five mile, etc.),

β_4 is a vector of *v* parameter estimates for the IEW variables as compared to pre-construction transactions,

β_5 is a vector of *d* parameter estimates for the ISTA CE variables as compared to pre-announcement transactions, and

all other components are as defined in equation (1).

It is important to emphasize that the IEW and ISTA CE parameters in equation (6) have different reference categories than they do in the Base Model - equation (1). In the Base Model, ISTA CE and IEW are estimated in the post-construction period in reference to homes that sold outside of five miles and with no view of the turbines respectively.[75] In the All Sales Model, on the other hand, the coefficients for IEW (β_4) are estimated in reference to all <u>pre-construction</u> transactions (spanning the pre-announcement and post-announcement-pre-construction periods) and the coefficients for ISTA CE (β_5) are estimated in reference to all <u>pre-announcement</u> transactions. In making a distinction between the reference categories for IEW and ISTA CE, it is assumed that awareness of the view of turbines and awareness of

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[7] This might be the case if there is an Area Stigma that includes the reference homes.

[74] As discussed in footnote 47 on page 19, it is conceivable that awareness might occur prior to the announcement date used for this analysis. If true, this bias is likely to be sporadic in nature and less of an issue in this model, when all pre-announcement transactions are pooled (e.g., both transactions near and far away from where the turbines were eventually located) than in models presented later (e.g., temporal aspects model). onetheless, if present, this bias may weakly draw down the pre-announcement reference category.

[75] See Section 4.1 and also footnote 51 on page 24 for more information on why the post-construction dataset and five-mile-no-view homes reference category are used in the Base Model.

the distance from them might not occur at the same point in the development process. Specifically, it is assumed that IEW effects largely occur after the turbines are erected, in the post-construction period, but that ISTA CE effects might occur in the post-announcement-pre-construction timeframe. For example, after a wind facility is announced, it is not atypical for a map of the expected locations of the turbines to be circulated in the community, allowing home buyers and sellers to assess the distance of the planned facility from homes. Because of this assumed difference in when awareness begins for IEW and ISTA CE, the ISTA CE variable is populated for transactions occurring in the post-announcement-pre-construction period as well as the post-construction period (see Table 14 below), but the IEW variable is populated only for transactions in the post-construction period – as they were in the Base Model.[76]

Table 14: Frequency Summary for DISTANCE in All Sales Model

	< 0.57 Miles	0.57 - 1 Miles	1 - 3 Miles	3 - 5 Miles	> 5 Miles	Total
Post-Construction	67	58	2019	192	870	**4937**
Post-Announcement-Pre-Construction	1	7	40	277	1 0	**767**
TOTAL	**80**	**65**	**2359**	**2200**	**1000**	**5704**

ne beneficial consequence of the differences in reference categories for the IEW and ISTA CE variables in this model, as opposed to the Base Model, is that this model can accommodate all of the possible IEW and ISTA CE categories, including IEW transactions and transactions of homes outside of five miles. Because of the inclusion of these IEW and ISTA CE categories, the tests to investigate Area, Scenic ista, and uisance Stigmas are slightly different in this model than in the Base Model. For Area Stigma, for example, how homes with no view of the turbines fared can now be tested; if they are adversely affected by the presence of the wind facility, then this would imply a pervasive Area Stigma impact. For Scenic ista Stigma, the IEW coefficients (MI , M E ATE, etc.) can be compared (using a *t*-Test) to the IEW results; if they are significantly different, a Scenic ista Stigma would be an obvious culprit. Finally, for uisance Stigma, the ISTA CE coefficients inside of one mile can be compared (using a *t*-Test) to those outside of five miles; if there is a significant difference between these two categories of homes, then homes are likely affected by their proximity to the wind facility.

5.3.2. Analysis of Results

esults for the variables of interest for this hedonic model are summarized in Table 15, and Base Model results are shown for comparison purposes. (For brevity, the full set of results for the model is not shown in Table 15, but is instead included in Appendix H.) The adjusted ^{2} for the model is 0.75, down slightly from 0.77 for the Base Model, and indicating that this model has slightly more difficulty (i.e. less explanatory power) modeling transactions that occurred pre-

[76] It is conceivable that IEW effects could occur before the turbines are constructed. In some cases, for example, developers will simulate what the project will look like after construction during the post-announcement but pre-construction timeframe. In these situations, home buyers and sellers might adjust home values accordingly based on the expected views of turbines. It is assumed, however, that such adjustments are likely to be reasonably rare, and IEW effects are therefore estimated using only post-construction sales.

construction.[77] All study area, spatial adjustment, and home and site characteristics are significant at or above the one percent level and are similar in sign and magnitude to the estimates derived from the post-construction Base Model.

The IEW coefficients (β_4) are clearly affected by the change in reference category. All of the IEW parameter estimates are higher than the Base Model estimates for the same categories. f particular interest is the IEW coefficient, which represents the values of homes without a view of the turbines and that sold in the post-construction period, as compared to the mean value of homes that sold in the pre-construction period, all else being equal. These homes, on average, are estimated to sell for 2 (*p* value 0.08) more than similar pre-construction homes. If an Area Stigma existed, a negative coefficient for these IEW homes would be expected. Instead, a positive and statistically significant coefficient is found.[78] It is outside the ability of this study to determine whether the increase is directly related to the wind turbines, or whether some other factor is impacting these results, but in either instance, no evidence of a pervasive Area Stigma associated with the presence of the wind facilities is found.

To test for the possibility of Scenic ista Stigma, the coefficients for MI , M E ATE, SUBSTA TIAL, and E T EME views can be compared to the IEW coefficient using a simple *t*-Test. Table 16 presents these results. As shown, no significant difference is found for any of the IEW coefficients when compared to IEW transactions. This reinforces the findings earlier that, within the sample at least, there is no evidence of a Scenic ista Stigma.

The ISTA CE parameter estimates (β_5) are also found to be affected by the change in reference category, and all are lower than the Base Model estimates for the same categories. This result likely indicates that the inflation-adjusted mean value of homes in the pre-announcement period is slightly higher, on average, than for those homes sold outside of five miles in the post-construction period. This difference could be attributed to the inaccuracy of the inflation index, a pervasive effect from the wind turbines, or to some other cause. Because the coefficients are not systematically statistically significant, however, this result is not pursued further. What is of interest, however, is the negative 8 estimate for homes located between 000 feet and one mile of the nearest wind turbine (*p* value 0.0). To correctly interpret this result, and to compare it to the Base Model, one needs to discern if this coefficient is significantly different from the estimate for homes located outside of five miles, using a *t*-Test.

The results of this *t*-Test are shown in Table 17. The coefficient differences are found to be somewhat monotonically ordered. Moving from homes within 000 feet (-0.06, *p* value 0.22), and between 000 feet and one mile (-0.08, *p* value 0.04), to between one and three miles (0.00, *p* value 0.9) and between three and five miles (0.01, *p* value 0. 2) the ISTA CE coefficients are found to generally increase. onetheless, none of these coefficients are statistically significant except one, homes that sold between 000 feet and one mile. The latter finding suggests the possibility of uisance Stigma. It is somewhat unclear why an effect would be found in this model, however, when one was not evident in the Base Model. The most likely

[77] This slight change in performance is likely due to the inaccuracies of home and site characteristics and the inflation adjustment for homes that sold in the early part of the study period. This is discussed in more detail in footnote 50 on page 2 .

[78] For more on the significance level used for this report, see footnote 68 on page 0.

explanation is that the additional homes that are included in this model, specifically those homes that sold post-announcement but pre-construction, are driving the results. A thorough investigation of these temporal issues is provided in the next subsection.

In summation, no evidence is found of an Area or Scenic ista Stigma in this alternative hedonic model, but some limited not-conclusive evidence of a uisance Stigma is detected. To further explore the reliability of this latter result, the analysis now turns to the Temporal Aspects Model.

Table 15: Results from All Sales Model

	Base Model				All Sales			
Variables of Interest	**Coef**	**SE**	**p Value**	***n***	**Coef**	**SE**	**p Value**	***n***
Pre-Construction Sales	n/a	n/a	n/a	n/a	mitted	mitted	mitted	2,522
No View	mitted	mitted	mitted	4,207	0.02	0.01	0.08	4,207
Minor View	-0.01	0.01	0. 9	561	0.00	0.02	0.77	561
Moderate View	0.02	0.0	0.57	106	0.0	0.0	0.41	106
Substantial View	-0.01	0.07	0.92	5	0.0	0.07	0.5	5
Extreme View	0.02	0.09	0.77	28	0.06	0.08	0. 8	28
Inside 3000 Feet	-0.05	0.06	0. 1	67	-0.06	0.05	0.18	80
Between 3000 Feet and 1 Mile	-0.05	0.05	0.20	58	-0.08	0.05	0.0	65
Between 1 and 3 Miles	0.00	0.02	0.80	2,019	0.00	0.01	0.80	2, 59
Between 3 and 5 Miles	0.02	0.01	0.26	1,92	0.01	0.01	0.59	2,200
Outside 5 Miles	mitted	mitted	mitted	870	0.00	0.02	0.78	1,000
Pre-Announcement Sales	n/a	n/a	n/a	n/a	mitted	mitted	mitted	1,755

"Omitted" = reference category for fixed effects variables. "n" = number of cases in category when category = "1"

Model Information

Model Equation Number	**1**	**6**
Dependent Variable	**LN_SalePrice96**	**LN_SalePrice96**
Number of Cases	**4937**	**7459**
Number of Predictors (k)	**37**	**39**
F Statistic	**442.8**	**579.9**
Adjusted R Squared	**0.77**	**0.75**

Table 16: Results from Equality Test of VIEW Coefficients in the All Sales Model

	No View	**Minor View**	**Moderate View**	**Substantial View**	**Extreme View**
n	4,207	561	106	5	28
Coefficient	0.02	0.00	0.0	0.0	0.06
Coefficient Difference *	eference	-0.02	0.00	0.01	0.04
Variance	0.0001	0.000	0.0009	0.00 0	0.0050
Covariance	n/a	0.00011	0.00010	0.00009	0.00008
Df	n/a	7419	7419	7419	7419
***t*-Test**	n/a	-1.20	0.17	0.2	0.58
Significance	n/a	0.2	0.87	0.82	0.57

** Differences are rounded to the nearest second decimal place.*
"n" = number of cases in category when category = "1"

Table 17: Results from Equality Test of DISTANCE Coefficients in the All Sales Model

	Inside 3000 Feet	Between 3000 Feet and 1 Mile	Between 1 and 3 Miles	Between 3 and 5 Miles	Outside 5 Miles
n	80	65	2, 59	2,200	1,000
Coefficient	-0.06	-0.08	0.00	0.01	0.00
Coefficient Difference *	-0.05	-0.08	0.00	0.01	eference
Variance	0.0019	0.0015	0.0002	0.0002	0.000
Covariance	0.00010	0.0001	0.0001	0.00015	n/a
Df	7419	7419	7419	7419	n/a
***t* Test**	-1.2	-2.06	0.09	1.00	n/a
Significance	0.22	0.04	0.9	0. 2	n/a

** Differences are rounded to the nearest second decimal place.*
"n" = number of cases in category when category = "1"

5.4. Temporal Aspects Model

Based on the results of the All Sales Model, a more thorough investigation of how uisance and Area Stigma effects might change throughout the wind project development period is warranted. As discussed previously, there is some evidence that property value impacts may be particularly strong after the announcement of a disamenity, but then may fade with time as the community adjusts to the presence of that disamenity (e.g., Wolsink, 1989). The Temporal Aspects Model presented here allows for an investigation of how the different periods of the wind project development process affect estimates for the impact of ISTA CE on sales prices.

5.4.1. Dataset and Model Form

Here the full set of 7,459 residential transactions is used, allowing an exploration of potential property value impacts (focusing on the ISTA CE variable) throughout time, including in the pre-construction period. The following model is then estimated:

$$\ln(\mathrm{P}) = \beta_0 + \beta_1 \quad + \sum_{\mathrm{s}} \beta_2 \mathrm{S} + \sum_{\mathrm{k}} \beta \quad + \sum_{\mathrm{v}} \beta_4 \quad \mathrm{IEW} + \sum_{\mathrm{y}} \beta_5 (\quad \mathrm{ISTA} \quad \mathrm{CE} \cdot \mathrm{PE} \quad \mathrm{I} \quad) + \varepsilon \qquad (7)$$

where

ISTA CE is a vector of categorical distance variables (e.g., less than one mile, between one and three miles, etc.),

PE I is a vector of categorical development period variables (e.g., after announcement and before construction, etc.),

β_5 is a vector of *y* parameter estimates for each ISTA CE and PE I category as compared to the transactions more than two years before announcement and outside of five miles, and all other components are as defined in equation (1).

The PE I variable contains six different options:

1) More than two years before announcement;
2) Less than two years before announcement;
) After announcement but before construction;
4) Less than two years after construction;
5) Between two and four years after construction; and

6) More than four years after construction.

In contrast to the Base Model, the two ISTA CE categories inside of one mile are collapsed into a single less than one mile group. This approach increases the number of transactions in each crossed subcategory of data, and therefore enhances the stability of the parameter estimates and decreases the size of the standard errors, thus providing an increased opportunity to discover statistically significant effects. Therefore, in this model the ISTA CE variable contains four different options:

1) Less than one mile;
2) Between one and three miles;
) Between three and five miles; and
4) utside of five miles.[79]

The number of transactions in each of the ISTA CE and PE I categories is presented in Table 18.

The coefficients of interest are β_5, which represent the vector of marginal differences between homes sold at various distances from the wind facility (ISTA CE) during various periods of the development process (PE I) as compared to the reference group. The reference group in this model consists of transactions that occurred more than two years before the facility was announced for homes that were situated more than five miles from where the turbines were ultimately constructed. It is assumed that the value of these homes would not be affected by the future presence of the wind facility. The IEW parameters, although included in the model, are not interacted with PE I and therefore are treated as controlling variables.[80]

Although the comparisons of these categorical variables <u>between</u> different ISTA CE and PE I categories is be interesting, it is the comparison of coefficients <u>within</u> each PE I and ISTA CE category that is the focus of this section. Such comparisons, for example, allow one to compare how the average value of homes inside of one mile that sold two years before announcement compare to the average value of homes inside of one mile that sold in the post-announcement-pre-construction period. For this comparison, a *t*-Test similar to that in the All Sales Model is used.

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[79] For homes that sold in the pre-construction time frame, no turbines yet existed, and therefore ISTA CE is created using a proxy: the Euclidian distance to where the turbines were eventually constructed. This approach introduces some bias when there is more than one facility in the study area. Conceivably, a home that sold in the post-announcement-pre-construction period of one wind facility could also be assigned to the pre-announcement period of another facility in the same area. For this type of sale, it is not entirely clear which PE I and ISTA CE is most appropriate, but every effort was made to apply the sale to the wind facility that was most likely to have an impact. In most cases this meant choosing the closest facility, but in some cases, when development periods were separated by many years, simply the earliest facility was chosen. In general, any bias created by these judgments is expected to be minimal because, in the large majority of cases, the development process in each study area was more-or-less continuous and focused in a specific area rather then being spread widely apart.

[80] As discussed earlier, the IEW variable was considered most relevant for the post-construction period, so delineations based on development periods that extended into the pre-construction phase were unnecessary. It is conceivable, however, that IEW effects vary in periods following construction, such as in the first two years or after that. Although this is an interesting question, the numbers of cases for the SUBSTA TIAL and E T EME ratings – even if combined – when divided into the temporal periods were too small to be fruitful for analysis.

Table 18: Frequency Crosstab of DISTANCE and PERIOD

	More Than 2 Years Before Announcement	Less Than 2 Years Before Announcement	After Announcement Before Construction	Less Than 2 Years After Construction	Between 2 and 4 Years After Construction	More Than 4 Years After Construction	Total
Less Than 1 Mile	8	40	20	9	45	4	**225**
Between 1 and 3 Miles	28	592	40	806	502	709	**3,232**
Between 3 and 5 Miles	157	80	277	572	594	757	**2,737**
Outside of 5 Miles	1 2	1	1 0	218	227	425	**1,265**
TOTAL	**610**	**1,145**	**767**	**1,635**	**1,368**	**1,934**	**7,459**

5.4.2. Analysis of Results

esults for the variables of interest for this hedonic model are presented in Table 19; as with previous models, the full set of results is contained in Appendix H. Similar to the All Sales Model discussed in the previous section, the adjusted ^{2} for the model is 0.75, down slightly from 0.77 for the Base Model, and indicating that this model has slightly more difficulty (i.e., less explanatory power) modeling transactions that occurred before wind facility construction. All study area, spatial adjustment, and home and site characteristics are significant at or above the one percent level, are of the appropriate sign, and are similar in magnitude to the estimates derived from the post-construction Base Model.

All of the ISTA CE / PE I interaction coefficients for distances outside of one mile are relatively small (-0.04 β_5 0.02) and none are statistically significant. This implies that there are no statistically significant differences in property values between the reference category homes – homes sold more than two years before announcement that were situated outside of five miles from where turbines were eventually erected – and any of the categories of homes that sold outside of one mile at any other period in the wind project development process. These comparisons demonstrate, arguably more directly than any other model presented in this report that Area Stigma effects likely do not exist in the sample.

The possible presence of a uisance Stigma is somewhat harder to discern. For homes that sold inside of one mile of the nearest wind turbine, in three of the six periods there are statistically significant negative differences between average property values when compared to the reference category. Transactions completed more than two years before facility announcement are estimated to be valued at 1 less (*p* value 0.02) than the reference category, transactions less than two years before announcement are 10 lower (*p* value 0.06), and transactions after announcement but before construction are 14 lower (*p* value 0.04). For other periods, however, these marginal differences are considerably smaller and are not statistically different from the reference category. Sales prices in the first two years after construction are, on average, 9 less (*p* value 0.15), those occurring between three and four years following construction are, on average, 1 less (*p* value 0.86), and those occurring more than four years after construction are, on average, 7 less (*p* value 0. 7).

Table 19: Results from Temporal Aspects Model

Variables of Interest		Temporal Aspects			
		Coef	**SE**	**p Value**	***n***
Inside 1 Mile	**More Than 2 Years Before Announcement**	-0.1	0.06	0.02	8
	Less Than 2 Years Before Announcement	-0.10	0.05	0.06	40
	After Announcement Before Construction	-0.14	0.06	0.04	21
	2 Years After Construction	-0.09	0.07	0.11	9
	Between 2 and 4 Years After Construction	-0.01	0.06	0.85	44
	More Than 4 Years After Construction	-0.07	0.08	0.22	42
Between 1-3 Miles	**More Than 2 Years Before Announcement**	-0.04	0.0	0.18	28
	Less Than 2 Years Before Announcement	0.00	0.0	0.91	592
	After Announcement Before Construction	-0.02	0.0	0.54	42
	2 Years After Construction	0.00	0.0	0.90	807
	Between 2 and 4 Years After Construction	0.01	0.0	0.78	50
	More Than 4 Years After Construction	0.00	0.0	0.9	710
Between 3-5 Miles	**More Than 2 Years Before Announcement**	0.00	0.04	0.92	157
	Less Than 2 Years Before Announcement	0.00	0.0	0.97	80
	After Announcement Before Construction	0.00	0.0	0.9	299
	2 Years After Construction	0.02	0.0	0.55	574
	Between 2 and 4 Years After Construction	0.01	0.0	0.65	594
	More Than 4 Years After Construction	0.01	0.0	0.67	758
Outside 5 Miles	**More Than 2 Years Before Announcement**	mitted	mitted	mitted	1 2
	Less Than 2 Years Before Announcement	-0.0	0.04	0.	1
	After Announcement Before Construction	-0.0	0.0	0. 9	105
	2 Years After Construction	-0.0	0.0	0.44	215
	Between 2 and 4 Years After Construction	0.0	0.0	0.44	227
	More Than 4 Years After Construction	0.01	0.0	0.7	424

"Omitted" = reference category for fixed effects variables.
"n" indicates number of cases in category when category = "1"

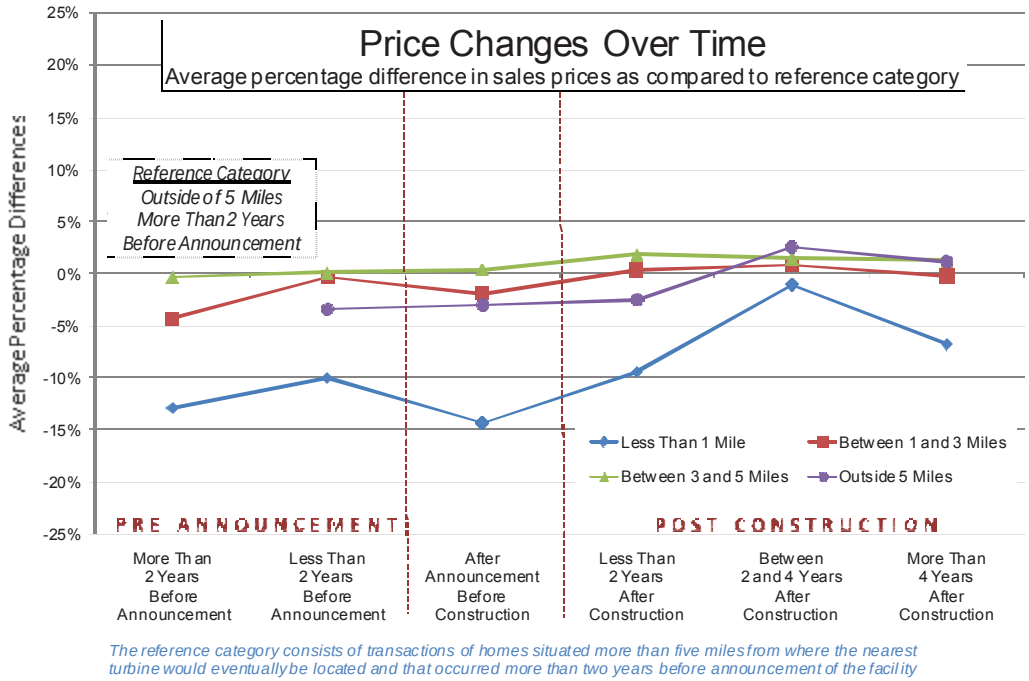
Model Information

Model Equation Number	**7**
Dependent Variable	**LN_SalePrice96**
Number of Cases	**7459**
Number of Predictors (k)	**56**
F Statistic	**404.5**
Adjusted R Squared	**0.75**

What these results suggest (as shown in Figure 8) is that homes inside of one mile in the sample, on average, were depressed in value (in relation to the reference category) before and after the announcement of the wind facility and up to the point that construction began, but that those values rebounded somewhat after construction commenced.[81] This conclusion also likely explains why a significant and negative effect for homes that sold between 000 feet and one mile is found in the All Sales Model presented in Section 5. : homes within this distance range that sold prior to facility construction were depressed in value and most likely drove the results for homes that sold after announcement. egardless, these results are not suggestive of a pervasive uisance Stigma.

[81] As discussed in footnotes 47 (on page 19) and 74 (on page 8), the announcement date often refers to the first time the proposed facility appeared in the press. Awareness of the project in the community may precede this date, however, and therefore transactions occurring in the period less than two years before announcement could conceivably have been influenced by the prospective wind project, but it is considerably less likely that those in the period more than two years before announcement would have been influenced.

Figure 8: Results from the Temporal Aspects Model



To explore Nuisance Stigma further, the analysis again turns to the *t*-Test and compares the coefficients for transactions that occurred more than two years before wind facility announcement (during which time the future wind facility is not expected to have any impact on sales prices) to the estimates for the DISTANCE coefficients in the periods that follow. These results are shown in Table 20. Focusing on those transactions inside of one mile, it is found that all coefficients are greater in magnitude than the reference category except during the post-announcement-pre-construction period (which is 1% less and is not statistically significant; *p* value 0.90), indicating, on average, that home values are increasing or staying stable from the pre-announcement reference period onward. These increases, however, are not statistically significant except in the period of two to four years after construction (0.12, *p* value 0.08). With respect to Nuisance Stigma, the more important result is that, relative to homes that sold well before the wind facility was announced, no statistically significant adverse effect is found in any period within a one mile radius of the wind facility. Therefore, the -5% (albeit not statistically significant) average difference that is found in the Base Model, and the -8% (statistically significant) result that is found in the All Sales Model (for homes between 0000 feet and one mile) appear to both be a reflection of depressed home prices that preceded the construction of the relevant wind facilities. If construction of the wind facilities were downwardly influencing the sales prices of these homes, as might be deduced from the Base or All Sales Models alone, a diminution in the inflation adjusted price would be seen as compared to pre-announcement levels. Instead, an increase is seen. As such, no persuasive evidence of a Nuisance Stigma is evident among this sample of transactions.[82]

[82] It should be noted that the numbers of study areas represented for homes situated inside of one mile but in the periods "more than two years before announcement" and "more than four years after construction" are fewer ($n = 5$) than in the other temporal categories ($n = 8$). Further, the "more than two years before announcement – inside of one mile" category is dominated by transactions from one study area ("KCC"). For these reasons, there is less

Technical Support Document: -
Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis -
Under Executive Order 12866 -

Interagency Working Group on Social Cost of Carbon, United States Government

With participation by

Council of Economic Advisers
Council on Environmental Quality
Department of Agriculture
Department of Commerce
Department of Energy
Department of Transportation
Environmental Protection Agency
National Economic Council
Office of Management and Budget
Office of Science and Technology Policy
Department of the Treasury

May 2013

Executive Summary

Under Executive Order 12866, agencies are required, to the extent permitted by law, "to assess both the costs and the benefits of the intended regulation and, recognizing that some costs and benefits are difficult to quantify, propose or adopt a regulation only upon a reasoned determination that the benefits of the intended regulation justify its costs." The purpose of the "social cost of carbon" (SCC) estimates presented here is to allow agencies to incorporate the social benefits of reducing carbon dioxide (CO_2) emissions into cost-benefit analyses of regulatory actions that impact cumulative global emissions. The SCC is an estimate of the monetized damages associated with an incremental increase in carbon emissions in a given year. It is intended to include (but is not limited to) changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services due to climate change.

The interagency process that developed the original U.S. government's SCC estimates is described in the 2010 interagency technical support document (TSD) (Interagency Working Group on Social Cost of Carbon 2010). Through that process the interagency group selected four SCC values for use in regulatory analyses. Three values are based on the average SCC from three integrated assessment models (IAMs), at discount rates of 2.5, 3, and 5 percent. The fourth value, which represents the 95th percentile SCC estimate across all three models at a 3 percent discount rate, is included to represent higher-than-expected impacts from temperature change further out in the tails of the SCC distribution.

While acknowledging the continued limitations of the approach taken by the interagency group in 2010, this document provides an update of the SCC estimates based on new versions of each IAM (DICE, PAGE, and FUND). It does not revisit other interagency modeling decisions (e.g., with regard to the discount rate, reference case socioeconomic and emission scenarios, or equilibrium climate sensitivity). Improvements in the way damages are modeled are confined to those that have been incorporated into the latest versions of the models by the developers themselves in the peer-reviewed literature.

The SCC estimates using the updated versions of the models are higher than those reported in the 2010 TSD. By way of comparison, the four 2020 SCC estimates reported in the 2010 TSD were $7, $26, $42 and $81 (2007$). The corresponding four updated SCC estimates for 2020 are $12, $43, $65, and $129 (2007$). The model updates that are relevant to the SCC estimates include: an explicit representation of sea level rise damages in the DICE and PAGE models; updated adaptation assumptions, revisions to ensure damages are constrained by GDP, updated regional scaling of damages, and a revised treatment of potentially abrupt shifts in climate damages in the PAGE model; an updated carbon cycle in the DICE model; and updated damage functions for sea level rise impacts, the agricultural sector, and reduced space heating requirements, as well as changes to the transient response of temperature to the buildup of GHG concentrations and the inclusion of indirect effects of methane emissions in the FUND model. The SCC estimates vary by year, and the following table summarizes the revised SCC estimates from 2010 through 2050.

Revised Social Cost of CO_2, 2010 – 2050 (in 2007 dollars per metric ton of CO_2)

Discount Rate Year	5.0% Avg	3.0% Avg	2.5% Avg	3.0% 95th
2010	11	33	52	90
2015	12	38	58	109
2020	12	43	65	129
2025	14	48	70	144
2030	16	52	76	159
2035	19	57	81	176
2040	21	62	87	192
2045	24	66	92	206
2050	27	71	98	221

I. Purpose

The purpose of this document is to update the schedule of social cost of carbon (SCC) estimates from the 2010 interagency technical support document (TSD) (Interagency Working Group on Social Cost of Carbon 2010).[1] E.O. 13563 commits the Administration to regulatory decision making "based on the best available science."[2] Additionally, the interagency group recommended in 2010 that the SCC estimates be revisited on a regular basis or as model updates that reflect the growing body of scientific and economic knowledge become available.[3] New versions of the three integrated assessment models used by the U.S. government to estimate the SCC (DICE, FUND, and PAGE), are now available and have been published in the peer reviewed literature. While acknowledging the continued limitations of the approach taken by the interagency group in 2010 (documented in the original 2010 TSD), this document provides an update of the SCC estimates based on the latest peer-reviewed version of the models, replacing model versions that were developed up to ten years ago in a rapidly evolving field. It does not revisit other assumptions with regard to the discount rate, reference case socioeconomic and emission scenarios, or equilibrium climate sensitivity. Improvements in the way damages are modeled are confined to those that have been incorporated into the latest versions of the models by the developers themselves in the peer-reviewed literature. The agencies participating in the interagency working group continue to investigate potential improvements to the way in which economic damages associated with changes in CO_2 emissions are quantified.

Section II summarizes the major updates relevant to SCC estimation that are contained in the new versions of the integrated assessment models released since the 2010 interagency report. Section III presents the updated schedule of SCC estimates for 2010 – 2050 based on these versions of the models. Section IV provides a discussion of other model limitations and research gaps.

II. Summary of Model Updates

This section briefly summarizes changes to the most recent versions of the three integrated assessment models (IAMs) used by the interagency group in 2010. We focus on describing those model updates that are relevant to estimating the social cost of carbon, as summarized in Table 1. For example, both the DICE and PAGE models now include an explicit representation of sea level rise damages. Other revisions to PAGE include: updated adaptation assumptions, revisions to ensure damages are constrained by GDP, updated regional scaling of damages, and a revised treatment of potentially abrupt shifts in climate damages. The DICE model's simple carbon cycle has been updated to be more consistent with a more complex climate model. The FUND model includes updated damage functions for sea level rise impacts, the agricultural sector, and reduced space heating requirements, as well as changes to the transient response of temperature to the buildup of GHG concentrations and the inclusion of indirect effects of

[1] In this document, we present all values of the SCC as the cost per metric ton of CO_2 emissions. Alternatively, one could report the SCC as the cost per metric ton of carbon emissions. The multiplier for translating between mass of CO_2 and the mass of carbon is 3.67 (the molecular weight of CO_2 divided by the molecular weight of carbon = 44/12 = 3.67).

[2] http://www.whitehouse.gov/sites/default/files/omb/inforeg/eo12866/eo13563_01182011.pdf

[3] See p. 1, 3, 4, 29, and 33 (Interagency Working Group on Social Cost of Carbon 2010).

methane emissions. Changes made to parts of the models that are superseded by the interagency working group's modeling assumptions – regarding equilibrium climate sensitivity, discounting, and socioeconomic variables – are not discussed here but can be found in the references provided in each section below.

Table 1: Summary of Key Model Revisions Relevant to the Interagency SCC

IAM	Version used in 2010 Interagency Analysis	New Version	Key changes relevant to interagency SCC
DICE	2007	2010	Updated calibration of the carbon cycle model and explicit representation of sea level rise (SLR) and associated damages.
FUND	3.5 (2009)	3.8 (2012)	Updated damage functions for space heating, SLR, agricultural impacts, changes to transient response of temperature to buildup of GHG concentrations, and inclusion of indirect climate effects of methane.
PAGE	2002	2009	Explicit representation of SLR damages, revisions to damage function to ensure damages do not exceed 100% of GDP, change in regional scaling of damages, revised treatment of potential abrupt damages, and updated adaptation assumptions.

A. DICE

DICE 2010 includes a number of changes over the previous 2007 version used in the 2010 interagency report. The model changes that are relevant for the SCC estimates developed by the interagency working group include: 1) updated parameter values for the carbon cycle model, 2) an explicit representation of sea level dynamics, and 3) a re-calibrated damage function that includes an explicit representation of economic damages from sea level rise. Changes were also made to other parts of the DICE model—including the equilibrium climate sensitivity parameter, the rate of change of total factor productivity, and the elasticity of the marginal utility of consumption—but these components of DICE are superseded by the interagency working group's assumptions and so will not be discussed here. More details on DICE2007 can be found in Nordhaus (2008) and on DICE2010 in Nordhaus (2010). The DICE2010 model and documentation is also available for download from the homepage of William Nordhaus.

Carbon Cycle Parameters

DICE uses a three-box model of carbon stocks and flows to represent the accumulation and transfer of carbon among the atmosphere, the shallow ocean and terrestrial biosphere, and the deep ocean. These parameters are "calibrated to match the carbon cycle in the Model for the Assessment of Greenhouse

Gas Induced Climate Change (MAGICC)" (Nordhaus 2008 p 44).[4] Carbon cycle transfer coefficient values in DICE2010 are based on re-calibration of the model to match the newer 2009 version of MAGICC (Nordhaus 2010 p 2). For example, in DICE2010, in each decade, 12 percent of the carbon in the atmosphere is transferred to the shallow ocean, 4.7 percent of the carbon in the shallow ocean is transferred to the atmosphere, 94.8 percent remains in the shallow ocean, and 0.5 percent is transferred to the deep ocean. For comparison, in DICE 2007, 18.9 percent of the carbon in the atmosphere is transferred to the shallow ocean each decade, 9.7 percent of the carbon in the shallow ocean is transferred to the atmosphere, 85.3 percent remains in the shallow ocean, and 5 percent is transferred to the deep ocean.

The implication of these changes for DICE2010 is in general a weakening of the ocean as a carbon sink and therefore a higher concentration of carbon in the atmosphere than in DICE2007, for a given path of emissions. All else equal, these changes will generally increase the level of warming and therefore the SCC estimates in DICE2010 relative to those from DICE2007.

Sea Level Dynamics

A new feature of DICE2010 is an explicit representation of the dynamics of the global average sea level anomaly to be used in the updated damage function (discussed below). This section contains a brief description of the sea level rise (SLR) module; a more detailed description can be found on the model developer's website.[5] The average global sea level anomaly is modeled as the sum of four terms that represent contributions from: 1) thermal expansion of the oceans, 2) melting of glaciers and small ice caps, 3) melting of the Greenland ice sheet, and 4) melting of the Antarctic ice sheet.

The parameters of the four components of the SLR module are calibrated to match consensus results from the IPCC's Fourth Assessment Report (AR4).[6] The rise in sea level from thermal expansion in each time period (decade) is 2 percent of the difference between the sea level in the previous period and the long run equilibrium sea level, which is 0.5 meters per degree Celsius (°C) above the average global temperature in 1900. The rise in sea level from the melting of glaciers and small ice caps occurs at a rate of 0.008 meters per decade per °C above the average global temperature in 1900.

The contribution to sea level rise from melting of the Greenland ice sheet is more complex. The equilibrium contribution to SLR is 0 meters for temperature anomalies less than 1 °C and increases linearly from 0 meters to a maximum of 7.3 meters for temperature anomalies between 1 °C and 3.5 °C. The contribution to SLR in each period is proportional to the difference between the previous period's sea level anomaly and the equilibrium sea level anomaly, where the constant of proportionality increases with the temperature anomaly in the current period.

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[4] MAGICC is a simple climate model initially developed by the U.S. National Center for Atmospheric Research that has been used heavily by the Intergovernmental Panel on Climate Change (IPCC) to emulate projections from more sophisticated state of the art earth system simulation models (Randall et al. 2007).

[5] Documentation on the new sea level rise module of DICE is available on William Nordhaus' website at: http://nordhaus.econ.yale.edu/documents/SLR_021910.pdf.

[6] For a review of post-IPCC AR4 research on sea level rise, see Nicholls et al. (2011) and NAS (2011).

The contribution to SLR from the melting of the Antarctic ice sheet is -0.001 meters per decade when the temperature anomaly is below 3 °C and increases linearly between 3 °C and 6 °C to a maximum rate of 0.025 meters per decade at a temperature anomaly of 6 °C.

Re-calibrated Damage Function

Economic damages from climate change in the DICE model are represented by a fractional loss of gross economic output in each period. A portion of the remaining economic output in each period (net of climate change damages) is consumed and the remainder is invested in the physical capital stock to support future economic production, so each period's climate damages will reduce consumption in that period and in all future periods due to the lost investment. The fraction of output in each period that is lost due to climate change impacts is represented as one minus a fraction, which is one divided by a quadratic function of the temperature anomaly, producing a sigmoid ("S"-shaped) function.[7] The loss function in DICE2010 has been expanded by adding a quadratic function of SLR to the quadratic function of temperature. In DICE2010 the temperature anomaly coefficients have been recalibrated to avoid double-counting damages from sea level rise that were implicitly included in these parameters in DICE2007.

The aggregate damages in DICE2010 are illustrated by Nordhaus (2010 p 3), who notes that "…damages in the uncontrolled (baseline) [i.e., reference] case … in 2095 are $12 trillion, or 2.8 percent of global output, for a global temperature increase of 3.4 °C above 1900 levels." This compares to a loss of 3.2 percent of global output at 3.4 °C in DICE2007. However, in DICE2010, annual damages are lower in most of the early periods of the modeling horizon but higher in later periods than would be calculated using the DICE2007 damage function. Specifically, the percent difference between damages in the base run of DICE2010 and those that would be calculated using the DICE2007 damage function starts at +7 percent in 2005, decreases to a low of -14 percent in 2065, then continuously increases to +20 percent by 2300 (the end of the interagency analysis time horizon), and to +160 percent by the end of the model time horizon in 2595. The large increases in the far future years of the time horizon are due to the permanence associated with damages from sea level rise, along with the assumption that the sea level is projected to continue to rise long after the global average temperature begins to decrease. The changes to the loss function generally decrease the interagency working group SCC estimates slightly given that relative increases in damages in later periods are discounted more heavily, all else equal.

B. FUND

FUND version 3.8 includes a number of changes over the previous version 3.5 (Narita et al. 2010) used in the 2010 interagency report. Documentation supporting FUND and the model's source code for all versions of the model is available from the model authors.[8] Notable changes, due to their impact on the

[7] The model and documentation, including formulas, are available on the author's webpage at http://www.econ.yale.edu/~nordhaus/homepage/RICEmodels.htm.

[8] http://www.fund-model.org/. This report uses version 3.8 of the FUND model, which represents a modest update to the most recent version of the model to appear in the literature (version 3.7) (Anthoff and Tol, 2013). For the purpose of computing the SCC, the relevant changes (between 3.7 to 3.8) are associated with improving

SCC estimates, are adjustments to the space heating, agriculture, and sea level rise damage functions in addition to changes to the temperature response function and the inclusion of indirect effects from methane emissions.[9] We discuss each of these in turn.

Space Heating

In FUND, the damages associated with the change in energy needs for space heating are based on the estimated impact due to one degree of warming. These baseline damages are scaled based on the forecasted temperature anomaly's deviation from the one degree benchmark and adjusted for changes in vulnerability due to economic and energy efficiency growth. In FUND 3.5, the function that scales the base year damages adjusted for vulnerability allows for the possibility that in some simulations the benefits associated with reduced heating needs may be an unbounded convex function of the temperature anomaly. In FUND 3.8, the form of the scaling has been modified to ensure that the function is everywhere concave and that there will exist an upper bound on the benefits a region may receive from reduced space heating needs. The new formulation approaches a value of two in the limit of large temperature anomalies, or in other words, assuming no decrease in vulnerability, the reduced expenditures on space heating at any level of warming will not exceed two times the reductions experienced at one degree of warming. Since the reduced need for space heating represents a benefit of climate change in the model, or a negative damage, this change will increase the estimated SCC. This update accounts for a significant portion of the difference in the expected SCC estimates reported by the two versions of the model when run probabilistically.

Sea Level Rise and Land Loss

The FUND model explicitly includes damages associated with the inundation of dry land due to sea level rise. The amount of land lost within a region is dependent upon the proportion of the coastline being protected by adequate sea walls and the amount of sea level rise. In FUND 3.5 the function defining the potential land lost in a given year due to sea level rise is linear in the rate of sea level rise for that year. This assumption implicitly assumes that all regions are well represented by a homogeneous coastline in length and a constant uniform slope moving inland. In FUND 3.8 the function defining the potential land lost has been changed to be a convex function of sea level rise, thereby assuming that the slope of the shore line increases moving inland. The effect of this change is to typically reduce the vulnerability of some regions to sea level rise based land loss, thereby lowering the expected SCC estimate. [10]

Agriculture

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consistency with IPCC AR4 by adjusting the atmospheric lifetimes of CH4 and N2O and incorporating the indirect forcing effects of CH4, along with making minor stability improvements in the sea wall construction algorithm.

[9] The other damage sectors (water resources, space cooling, land loss, migration, ecosystems, human health, and extreme weather) were not significantly updated.

[10] For stability purposes this report also uses an update to the model which assumes that regional coastal protection measures will be built to protect the most valuable land first, such that the marginal benefits of coastal protection is decreasing in the level of protection following Fankhauser (1995).

In FUND, the damages associated with the agricultural sector are measured as proportional to the sector's value. The fraction is bounded from above by one and is made up of three additive components that represent the effects from carbon fertilization, the rate of temperature change, and the level of the temperature anomaly. In both FUND 3.5 and FUND 3.8, the fraction of the sector's value lost due to the level of the temperature anomaly is modeled as a quadratic function with an intercept of zero. In FUND 3.5, the coefficients of this loss function are modeled as the ratio of two random normal variables. This specification had the potential for unintended extreme behavior as draws from the parameter in the denominator approached zero or went negative. In FUND 3.8, the coefficients are drawn directly from truncated normal distributions so that they remain in the range $[0,\infty)$ and $(-\infty,0]$, respectively, ensuring the correct sign and eliminating the potential for divide by zero errors. The means for the new distributions are set equal to the ratio of the means from the normal distributions used in the previous version. In general the impact of this change has been to decrease the range of the distribution while spreading out the distributions' mass over the remaining range relative to the previous version. The net effect of this change on the SCC estimates is difficult to predict.

Transient Temperature Response

The temperature response model translates changes in global levels of radiative forcing into the current expected temperature anomaly. In FUND, a given year's increase in the temperature anomaly is based on a mean reverting function where the mean equals the equilibrium temperature anomaly that would eventually be reached if that year's level of radiative forcing were sustained. The rate of mean reversion defines the rate at which the transient temperature approaches the equilibrium. In FUND 3.5, the rate of temperature response is defined as a decreasing linear function of equilibrium climate sensitivity to capture the fact that the progressive heat uptake of the deep ocean causes the rate to slow at higher values of the equilibrium climate sensitivity. In FUND 3.8, the rate of temperature response has been updated to a quadratic function of the equilibrium climate sensitivity. This change reduces the sensitivity of the rate of temperature response to the level of the equilibrium climate sensitivity, a relationship first noted by Hansen et al. (1985) based on the heat uptake of the deep ocean. Therefore in FUND 3.8, the temperature response will typically be faster than in the previous version. The overall effect of this change is likely to increase estimates of the SCC as higher temperatures are reached during the timeframe analyzed and as the same damages experienced in the previous version of the model are now experienced earlier and therefore discounted less.

Methane

The IPCC AR4 notes a series of indirect effects of methane emissions, and has developed methods for proxying such effects when computing the global warming potential of methane (Forster et al. 2007). FUND 3.8 now includes the same methods for incorporating the indirect effects of methane emissions. Specifically, the average atmospheric lifetime of methane has been set to 12 years to account for the feedback of methane emissions on its own lifetime. The radiative forcing associated with atmospheric methane has also been increased by 40% to account for its net impact on ozone production and stratospheric water vapor. All else equal, the effect of this increased radiative forcing will be to increase the estimated SCC values, due to greater projected temperature anomaly.

C. PAGE

PAGE09 (Hope 2013) includes a number of changes from PAGE2002, the version used in the 2010 SCC interagency report. The changes that most directly affect the SCC estimates include: explicitly modeling the impacts from sea level rise, revisions to the damage function to ensure damages are constrained by GDP, a change in the regional scaling of damages, a revised treatment for the probability of a discontinuity within the damage function, and revised assumptions on adaptation. The model also includes revisions to the carbon cycle feedback and the calculation of regional temperatures.[11] More details on PAGE09 can be found in Hope (2011a, 2011b, 2011c). A description of PAGE2002 can be found in Hope (2006).

Sea Level Rise

While PAGE2002 aggregates all damages into two categories – economic and non-economic impacts -, PAGE09 adds a third explicit category: damages from sea level rise. In the previous version of the model, damages from sea level rise were subsumed by the other damage categories. In PAGE09 sea level damages increase less than linearly with sea level under the assumption that land, people, and GDP are more concentrated in low-lying shoreline areas. Damages from the economic and non-economic sector were adjusted to account for the introduction of this new category.

Revised Damage Function to Account for Saturation

In PAGE09, small initial economic and non-economic benefits (negative damages) are modeled for small temperature increases, but all regions eventually experience economic damages from climate change, where damages are the sum of additively separable polynomial functions of temperature and sea level rise. Damages transition from this polynomial function to a logistic path once they exceed a certain proportion of remaining Gross Domestic Product (GDP) to ensure that damages do not exceed 100 percent of GDP. This differs from PAGE2002, which allowed Eastern Europe to potentially experience large benefits from temperature increases, and which also did not bound the possible damages that could be experienced.

Regional Scaling Factors

As in the previous version of PAGE, the PAGE09 model calculates the damages for the European Union (EU) and then, assumes that damages for other regions are proportional based on a given scaling factor. The scaling factor in PAGE09 is based on the length of a region's coastline relative to the EU (Hope 2011b). Because of the long coastline in the EU, other regions are, on average, less vulnerable than the EU for the same sea level and temperature increase, but all regions have a positive scaling factor. PAGE2002 based its scaling factors on four studies reported in the IPCC's third assessment report, and allowed for benefits from temperature increase in Eastern Europe, smaller impacts in developed countries, and higher damages in developing countries.

[11] Because several changes in the PAGE model are structural (e.g., the addition of sea level rise and treatment of discontinuity), it is not possible to assess the direct impact of each change on the SCC in isolation as done for the other two models above.

Probability of a Discontinuity

In PAGE2002, the damages associated with a "discontinuity" (nonlinear extreme event) were modeled as an expected value. Specifically, a stochastic probability of a discontinuity was multiplied by the damages associated with a discontinuity to obtain an expected value, and this was added to the economic and non-economic impacts. That is, additional damages from an extreme event, such as extreme melting of the Greenland ice sheet, were multiplied by the probability of the event occurring and added to the damage estimate. In PAGE09, the probability of discontinuity is treated as a discrete event for each year in the model. The damages for each model run are estimated either with or without a discontinuity occurring, rather than as an expected value. A large-scale discontinuity becomes possible when the temperature rises beyond some threshold value between 2 and 4°C. The probability that a discontinuity will occur beyond this threshold then increases by between 10 and 30 percent for every 1°C rise in temperature beyond the threshold. If a discontinuity occurs, the EU loses an additional 5 to 25 percent of its GDP (drawn from a triangular distribution with a mean of 15 percent) in addition to other damages, and other regions lose an amount determined by the regional scaling factor. The threshold value for a possible discontinuity is lower than in PAGE2002, while the rate at which the probability of a discontinuity increases with the temperature anomaly and the damages that result from a discontinuity are both higher than in PAGE2002. The model assumes that only one discontinuity can occur and that the impact is phased in over a period of time, but once it occurs, its effect is permanent.

Adaptation

As in PAGE2002, adaptation is available to help mitigate any climate change impacts that occur. In PAGE this adaptation is the same regardless of the temperature change or sea level rise and is therefore akin to what is more commonly considered a reduction in vulnerability. It is modeled by reducing the damages by some percentage. PAGE09 assumes a smaller decrease in vulnerability than the previous version of the model and assumes that it will take longer for this change in vulnerability to be realized. In the aggregated economic sector, at the time of full implementation, this adaptation will mitigate all damages up to a temperature increase of 1°C, and for temperature anomalies between 1°C and 2°C, it will reduce damages by 15-30 percent (depending on the region). However, it takes 20 years to fully implement this adaptation. In PAGE2002, adaptation was assumed to reduce economic sector damages up to 2°C by 50-90 percent after 20 years. Beyond 2°C, no adaptation is assumed to be available to mitigate the impacts of climate change. For the non-economic sector, in PAGE09 adaptation is available to reduce 15 percent of the damages due to a temperature increase between 0°C and 2°C and is assumed to take 40 years to fully implement, instead of 25 percent of the damages over 20 years assumed in PAGE2002. Similarly, adaptation is assumed to alleviate 25-50 percent of the damages from the first 0.20 to 0.25 meters of sea level rise but is assumed to be ineffective thereafter. Hope (2011c) estimates that the less optimistic assumptions regarding the ability to offset impacts of temperature and sea level rise via adaptation increase the SCC by approximately 30 percent.

Other Noteworthy Changes

Two other changes in the model are worth noting. There is a change in the way the model accounts for decreased CO_2 absorption on land and in the ocean as temperature rises. PAGE09 introduces a linear feedback from global mean temperature to the percentage gain in the excess concentration of CO_2, capped at a maximum level. In PAGE2002, an additional amount was added to the CO_2 emissions each period to account for a decrease in ocean absorption and a loss of soil carbon. Also updated is the method by which the average global and annual temperature anomaly is downscaled to determine annual average regional temperature anomalies to be used in the regional damage functions. In PAGE2002, the scaling was determined solely based on regional difference in emissions of sulfate aerosols. In PAGE09, this regional temperature anomaly is further adjusted using an additive factor that is based on the average absolute latitude of a region relative to the area weighted average absolute latitude of the Earth's landmass, to capture relatively greater changes in temperature forecast to be experienced at higher latitudes.

III. Revised SCC Estimates

The updated versions of the three integrated assessment models were run using the same methodology detailed in the 2010 TSD (Interagency Working Group on Social Cost of Carbon 2010). The approach along with the inputs for the socioeconomic emissions scenarios, equilibrium climate sensitivity distribution, and discount rate remains the same. This includes the five reference scenarios based on the EMF-22 modeling exercise, the Roe and Baker equilibrium climate sensitivity distribution calibrated to the IPCC AR4, and three constant discount rates of 2.5, 3, and 5 percent.

As was previously the case, the use of three models, three discount rates, and five scenarios produces 45 separate distributions for the global SCC. The approach laid out in the 2010 TSD applied equal weight to each model and socioeconomic scenario in order to reduce the dimensionality down to three separate distributions representative of the three discount rates. The interagency group selected four values from these distributions for use in regulatory analysis. Three values are based on the average SCC across models and socio-economic-emissions scenarios at the 2.5, 3, and 5 percent discount rates, respectively. The fourth value was chosen to represent the higher-than-expected economic impacts from climate change further out in the tails of the SCC distribution. For this purpose, the 95th percentile of the SCC estimates at a 3 percent discount rate was chosen. (A detailed set of percentiles by model and scenario combination and additional summary statistics for the 2020 values is available in the Appendix.) As noted in the 2010 TSD, "the 3 percent discount rate is the central value, and so the central value that emerges is the average SCC across models at the 3 percent discount rate" (Interagency Working Group on Social Cost of Carbon 2010, p. 25). However, for purposes of capturing the uncertainties involved in regulatory impact analysis, the interagency group emphasizes the importance and value of including all four SCC values.

Table 2 shows the four selected SCC estimates in five year increments from 2010 to 2050. Values for 2010, 2020, 2030, 2040, and 2050 are calculated by first combining all outputs (10,000 estimates per

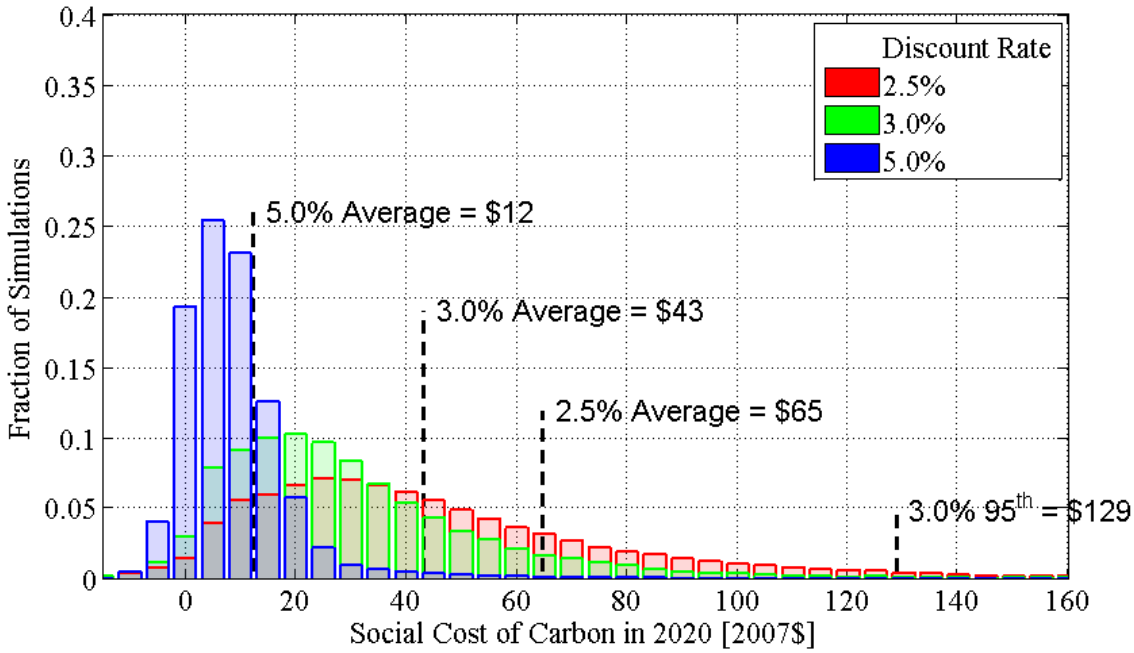
model run) from all scenarios and models for a given discount rate. Values for the years in between are calculated using linear interpolation. The full set of revised annual SCC estimates between 2010 and 2050 is reported in the Appendix.

Table 2: Revised Social Cost of CO_2, 2010 – 2050 (in 2007 dollars per metric ton of CO_2)

Discount Rate Year	5.0% Avg	3.0% Avg	2.5% Avg	3.0% 95th
2010	11	33	52	90
2015	12	38	58	109
2020	12	43	65	129
2025	14	48	70	144
2030	16	52	76	159
2035	19	57	81	176
2040	21	62	87	192
2045	24	66	92	206
2050	27	71	98	221

The SCC estimates using the updated versions of the models are higher than those reported in the 2010 TSD due to the changes to the models outlined in the previous section. By way of comparison, the 2020 SCC estimates reported in the original TSD were $7, $26, $42 and $81 (2007$) (Interagency Working Group on Social Cost of Carbon 2010). Figure 1 illustrates where the four SCC values for 2020 fall within the full distribution for each discount rate based on the combined set of runs for each model and scenario (150,000 estimates in total for each discount rate). In general, the distributions are skewed to the right and have long tails. The Figure also shows that the lower the discount rate, the longer the right tail of the distribution.

Figure 1: Distribution of SCC Estimates for 2020 (in 2007$ per metric ton CO_2)



As was the case in the 2010 TSD, the SCC increases over time because future emissions are expected to produce larger incremental damages as physical and economic systems become more stressed in response to greater climatic change. The approach taken by the interagency group is to compute the cost of a marginal ton emitted in the future by running the models for a set of perturbation years out to 2050. Table 3 illustrates how the growth rate for these four SCC estimates varies over time.

Table 3: Average Annual Growth Rates of SCC Estimates between 2010 and 2050

Average Annual Growth Rate (%)	5.0% Avg	3.0% Avg	2.5% Avg	3.0% 95th
2010-2020	1.2%	3.2%	2.4%	4.3%
2020-2030	3.4%	2.1%	1.7%	2.4%
2030-2040	3.0%	1.8%	1.5%	2.0%
2040-2050	2.6%	1.6%	1.3%	1.5%

The future monetized value of emission reductions in each year (the SCC in year *t* multiplied by the change in emissions in year *t*) must be discounted to the present to determine its total net present value for use in regulatory analysis. As previously discussed in the 2010 TSD, damages from future emissions should be discounted at the same rate as that used to calculate the SCC estimates themselves to ensure internal consistency – i.e., future damages from climate change, whether they result from emissions today or emissions in a later year, should be discounted using the same rate.

Under current OMB guidance contained in Circular A-4, analysis of economically significant proposed and final regulations from the domestic perspective is required, while analysis from the international perspective is optional. However, the climate change problem is highly unusual in at least two respects. First, it involves a global externality: emissions of most greenhouse gases contribute to damages around

the world even when they are emitted in the United States. Consequently, to address the global nature of the problem, the SCC must incorporate the full (global) damages caused by GHG emissions. Second, climate change presents a problem that the United States alone cannot solve. Even if the United States were to reduce its greenhouse gas emissions to zero, that step would be far from enough to avoid substantial climate change. Other countries would also need to take action to reduce emissions if significant changes in the global climate are to be avoided. Emphasizing the need for a global solution to a global problem, the United States has been actively involved in seeking international agreements to reduce emissions and in encouraging other nations, including emerging major economies, to take significant steps to reduce emissions. When these considerations are taken as a whole, the interagency group concluded that a global measure of the benefits from reducing U.S. emissions is preferable. For additional discussion, see the 2010 TSD.

IV. Other Model Limitations and Research Gaps

The 2010 interagency SCC TSD discusses a number of important limitations for which additional research is needed. In particular, the document highlights the need to improve the quantification of both non-catastrophic and catastrophic damages, the treatment of adaptation and technological change, and the way in which inter-regional and inter-sectoral linkages are modeled. While the new version of the models discussed above offer some improvements in these areas, further work remains warranted. The 2010 TSD also discusses the need to more carefully assess the implications of risk aversion for SCC estimation as well as the inability to perfectly substitute between climate and non-climate goods at higher temperature increases, both of which have implications for the discount rate used. EPA, DOE, and other agencies continue to engage in research on modeling and valuation of climate impacts that can potentially improve SCC estimation in the future.

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Appendix

Table A1: Annual SCC Values: 2010-2050 (2007$/metric ton CO_2)

Discount Rate Year	5.0% Avg	3.0% Avg	2.5% Avg	3.0% 95th
2010	11	33	52	90
2011	11	34	54	94
2012	11	35	55	98
2013	11	36	56	102
2014	11	37	57	106
2015	12	38	58	109
2016	12	39	60	113
2017	12	40	61	117
2018	12	41	62	121
2019	12	42	63	125
2020	12	43	65	129
2021	13	44	66	132
2022	13	45	67	135
2023	13	46	68	138
2024	14	47	69	141
2025	14	48	70	144
2026	15	49	71	147
2027	15	49	72	150
2028	15	50	73	153
2029	16	51	74	156
2030	16	52	76	159
2031	17	53	77	163
2032	17	54	78	166
2033	18	55	79	169
2034	18	56	80	172
2035	19	57	81	176
2036	19	58	82	179
2037	20	59	84	182
2038	20	60	85	185
2039	21	61	86	188
2040	21	62	87	192
2041	22	63	88	195
2042	22	64	89	198
2043	23	65	90	200
2044	23	65	91	203
2045	24	66	92	206
2046	24	67	94	209
2047	25	68	95	212
2048	25	69	96	215
2049	26	70	97	218
2050	27	71	98	221

Table A2: 2020 Global SCC Estimates at 2.5 Percent Discount Rate (2007$/metric ton CO_2)

Percentile	1st	5th	10th	25th	50th	Avg	75th	90th	95th	99th
Scenario[12]	PAGE									
IMAGE	6	11	15	27	58	129	139	327	515	991
MERGE	4	6	9	16	34	78	82	196	317	649
MESSAGE	4	8	11	20	42	108	107	278	483	918
MiniCAM Base	5	9	12	22	47	107	113	266	431	872
5th Scenario	2	4	6	11	25	85	68	200	387	955
Scenario	DICE									
IMAGE	25	31	37	47	64	72	92	123	139	161
MERGE	14	18	20	26	36	40	50	65	74	85
MESSAGE	20	24	28	37	51	58	71	95	109	221
MiniCAM Base	20	25	29	38	53	61	76	102	117	135
5th Scenario	17	22	25	33	45	52	65	91	106	126
Scenario	FUND									
IMAGE	-17	-1	5	17	34	44	59	90	113	176
MERGE	-7	2	7	16	30	35	49	72	91	146
MESSAGE	-19	-4	2	12	27	32	46	70	87	135
MiniCAM Base	-9	1	8	18	35	45	59	87	108	172
5th Scenario	-30	-12	-5	6	19	24	35	57	72	108

Table A3: 2020 Global SCC Estimates at 3 Percent Discount Rate (2007$/metric ton CO_2)

Percentile	1st	5th	10th	25th	50th	Avg	75th	90th	95th	99th
Scenario	PAGE									
IMAGE	4	7	10	18	38	91	95	238	385	727
MERGE	2	4	6	11	23	56	58	142	232	481
MESSAGE	3	5	7	13	29	75	74	197	330	641
MiniCAM Base	3	5	8	14	30	73	75	184	300	623
5th Scenario	1	3	4	7	17	58	48	136	264	660
Scenario	DICE									
IMAGE	16	21	24	32	43	48	60	79	90	102
MERGE	10	13	15	19	25	28	35	44	50	58
MESSAGE	14	18	20	26	35	40	49	64	73	83
MiniCAM Base	13	17	20	26	35	39	49	65	73	85
5th Scenario	12	15	17	22	30	34	43	58	67	79
Scenario	FUND									
IMAGE	-14	-3	1	9	20	25	35	54	69	111
MERGE	-8	-1	3	9	18	22	31	47	60	97
MESSAGE	-16	-5	-1	6	16	18	28	43	55	88
MiniCAM Base	-9	-1	3	10	21	27	35	53	67	107
5th Scenario	-22	-10	-5	2	10	13	20	33	42	63

[12] See 2010 TSD for a description of these scenarios.

Table A4: 2020 Global SCC Estimates at 5 Percent Discount Rate (2007$/metric ton CO_2)

Percentile	1st	5th	10th	25th	50th	Avg	75th	90th	95th	99th
Scenario	PAGE									
IMAGE	1	2	2	5	10	28	27	71	123	244
MERGE	1	1	2	3	7	17	17	45	75	153
MESSAGE	1	1	2	4	9	24	22	60	106	216
MiniCAM Base	1	1	2	3	8	21	21	54	94	190
5th Scenario	0	1	1	2	5	18	14	41	78	208
Scenario	DICE									
IMAGE	6	8	9	11	14	15	18	22	25	27
MERGE	4	5	6	7	9	10	12	15	16	18
MESSAGE	6	7	8	10	12	13	16	20	22	25
MiniCAM Base	5	6	7	8	11	12	14	18	20	22
5th Scenario	5	6	6	8	10	11	14	17	19	21
Scenario	FUND									
IMAGE	-9	-5	-3	-1	2	3	6	11	15	25
MERGE	-6	-3	-2	0	3	4	7	12	16	27
MESSAGE	-10	-6	-4	-1	2	2	5	9	13	23
MiniCAM Base	-7	-3	-2	0	3	4	7	11	15	26
5th Scenario	-11	-7	-5	-2	0	0	3	6	8	14

Table A5: Additional Summary Statistics of 2020 Global SCC Estimates

Discount rate:	5.0%				3.0%				2.5%			
Statistic:	Mean	Variance	Skewness	Kurtosis	Mean	Variance	Skewness	Kurtosis	Mean	Variance	Skewness	Kurtosis
DICE	12	26	2	15	38	409	3	24	57	1097	3	30
PAGE	22	1616	5	32	71	14953	4	22	101	29312	4	23
FUND	3	560	-170	35222	21	22487	-85	18842	36	68055	-46	13105

STATE OF FAILURE

HOW STATES FAIL TO PROTECT OUR HEALTH AND DRINKING WATER FROM TOXIC COAL ASH

37 COAL ASH REGULATORY PROGRAMS THAT PLACE OUR AIR, WATER AND HEALTH IN DANGER

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Cover Photo: Coal ash spill in Forward Township, PA, January 2005.

STATE OF FAILURE

How States Fail to Protect Our Health and Drinking Water from Toxic Coal Ash

Introduction: An Unhealthy Union

Coal ash is the second largest industrial waste stream in the United States. More than 140 million tons of coal ash, comprised of fly ash, bottom ash, boiler slag and flue gas desulfurization (FGD) sludge, are generated annually by the nation's coal-fired power plants. Coal ash contains a long list of carcinogenic and neurotoxic chemicals such as arsenic, lead, hexavalent chromium, cadmium and mercury. The toxic brew is stored in more than a thousand unstable ponds and landfills, which are located in nearly every state in the nation. **Yet most states don't have regulations in place to keep these toxic chemicals safely entombed and out of our air and drinking water.**

Earthjustice and Appalachian Mountain Advocates (AMA) uncovered the details of this state of failure in an exhaustive review of state regulations in 37 states, which together comprise over 98 percent of all the coal ash generated nationally. Our analysis debunks the oft-repeated myth that state programs are doing a good job of safeguarding our air and water and protecting communities from catastrophic dam failure.

Our review reveals that most states do not require all coal ash landfills and ponds to employ the most basic safeguards required at household trash landfills, such as composite liners, groundwater monitoring, leachate collection systems, dust controls and financial assurance; nor do states require that coal ash ponds be operated to avoid catastrophic collapse. In addition, most states allow the placement of toxic coal ash *in* water tables and the siting of ponds and landfills in wetlands, unstable areas and floodplains. When measured against basic safeguards that the U.S. Environmental Protection Agency (EPA) identified as essential to protect health and the environment,[1] state regulatory programs fail miserably to guarantee safety from contamination and catastrophe.

Although no rational person would question the necessity of lining and monitoring coal ash dumps to prevent the escape of toxic chemicals or the need to inspect the nation's aging fleet of nearly 700 coal ash dams, we found in the 37 states examined:

- Only 3 states require composite liners for all new coal ash ponds:
- Only 5 states require composite liners for all new coal ash landfills;
- Only 2 states require groundwater monitoring of all coal ash ponds;
- Only 4 states require groundwater monitoring of all coal ash landfills;
- Only 6 states prohibit siting of coal ash ponds into the water table; and
- Only 17 states require regulatory inspections of the structural integrity of coal ash ponds.

In view of the widespread absence of critical protections in most states, it is absolutely essential

that the EPA establish a national coal ash rule under subtitle C of the Resource Conservation and Recovery Act (RCRA). Currently, the EPA is at the threshold of a decision—it can continue to leave the regulation of this toxic waste entirely to states under subtitle D of RCRA, or it can establish national minimum standards under subtitle C of RCRA. Our analysis shows that it is far too dangerous to continue to allow states sole discretion over coal ash dumping. Nothing short of federally enforceable standards will protect our most vulnerable communities from continuing harm.

Amazingly, even the EPA readily admits that a state-controlled subtitle D scheme will continue to leave most communities without protections against precarious ponds and cancer-causing chemicals in their air and water. In fact, the EPA concludes that, based on the entrenched, decades-long state resistance to regulating coal ash, it expects **less than half** of the total ash generated in the U.S. to be governed by adequate state regulations, unless these regulations are made mandatory under a RCRA subtitle C rule.[2]

Part I of this report provides a brief overview of the threats posed by the widespread lack of state requirements for coal ash disposal. Part II explains how most state programs do not adequately protect public health and the environment from these threats by specifically identifying the regulatory gaps in 37 states. Part III identifies the 12 worst states; where regulations fail most completely to protect communities located near coal ash disposal sites, particularly coal ash ponds. Criteria for determining the most dangerous states include gross lack of basic regulatory safeguards, widespread dangerous disposal practices (especially wet disposal), and huge amounts of coal ash generated annually. By this measurement, the 12 worst states for coal ash disposal are (in alphabetical order): Alabama, Georgia, Illinois, Indiana, Kentucky, Missouri, North Carolina, Ohio, South Carolina, Tennessee, Texas, and Virginia.

PART I. WHAT'S AT STAKE:
Major Dam Failures, Unhealthy Air & Poisoned Water

Dangerous Dams: Another Accident Waiting to Happen

In Harriman, Tennessee on December 22, 2008, a coal ash dam at the Tennessee Valley Authority (TVA) Kingston Fossil Plant broke, releasing **1.1 billion** gallons of coal ash into the Emory and Clinch Rivers, destroying three homes and damaging a dozen others. By volume, this spill is the largest environmental disaster in U.S. history—100 times greater than the Exxon Valdez oil spill and 5 times larger than the BP Deepwater Horizon spill of 2010. While the cataclysmic disaster in Kingston is well known, few realize that **at least every three years since 2002, major breaks in coal ash ponds have occurred,** causing the release of millions of pounds of toxic sludge to waterways and drinking water sources. For example:

- In Euharlee, Georgia on July 28, 2002, a four-acre sinkhole fractured a coal ash pond at Georgia Power's Plant Bowen and caused the release of more than **2 million**

pounds of arsenic-laden coal ash to the Etowah River, a drinking water source for Rome, Georgia,[3] a city with a population of nearly 35,000 residents. The discharge contained arsenic at concentrations more than 100 times the federal safe drinking water standard.

- In Martins Creek, Pennsylvania on August 23, 2005, a coal ash dam broke at PPL Generation's Martin's Creek Power Plant, releasing over **100 million gallons** of ash into the Delaware River.[4] The spill could not be contained for four days.

- In Martinsville, Indiana on February 14, 2007, internal and external levees breached at the Indianapolis Power and Light's Eagle Valley Generating Station, resulting in a discharge of **30 million gallons** of coal ash sluice liquid to the White River.[5]

- In Martinsville, Indiana on January 30, 2008, a second breach occurred at the 52-year-old earthen dam resulting in another **30 million gallon** discharge of coal ash sludge to the White River.[6] None of the released ash was recovered.

- And these were not the only major breaks. About a week after the 2008 spill in Kingston, a gypsum pond at TVA's Widow's Creek Fossil Plant in Alabama released 10,000 gallons of coal ash to the Tennessee River.[7] And just last fall, approximately 10 tons of coal ash flowed from an 8-foot by 22-foot breach in the ash pond at Progress Energy's Sutton Electric Plant near Wilmington, North Carolina.[8]

It has been almost three years since the last massive coal ash disaster—which means the clock is ticking on the next multi-million-gallon spill. Unfortunately, not nearly enough has been done to avert the next disaster. In the years following the Kingston spill, neither the EPA nor any state legislature has overhauled coal ash pond regulations. Hundreds of dangerous ponds remain virtually unregulated, and basic requirements for safe dam and pond management, such as routine inspections and emergency action plans are still not required at ash ponds across the U.S.

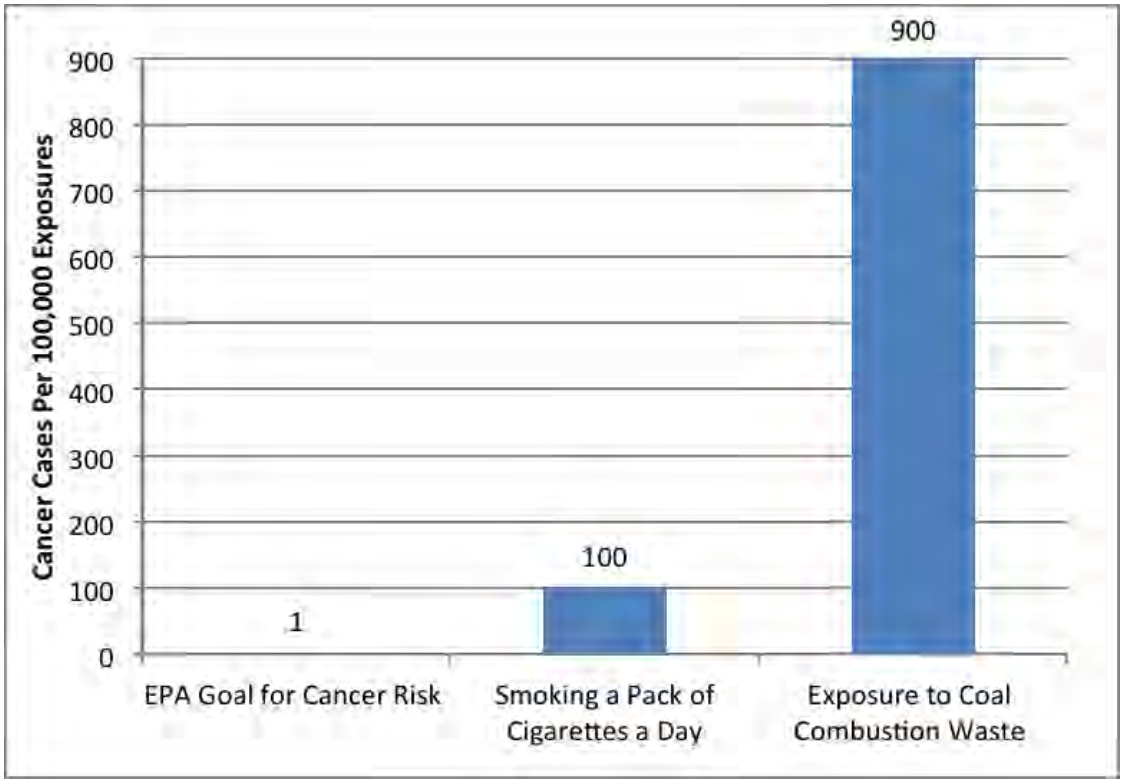
Poisoned Water and Air

While dramatic events like the coal ash spills garner national media attention, dangerous pollutants are quietly seeping from hundreds of improperly lined and unmonitored coal ash dumps into drinking water supplies and streams across the nation, exposing people and wildlife to toxic and cancer-causing substances. The vast majority of states do not require adequate monitoring or liners to stop or even detect the migration of pollution.

Coal ash contains numerous hazardous chemicals, including arsenic, cadmium, hexavalent chromium, lead, mercury and selenium.[9] The contaminants can cause cancer and damage the nervous system or other organs, especially in children. When coal ash comes into contact with water, these hazardous chemicals leach out of the ash and contaminate drinking water. [10] Over

137 cases of water contamination from coal ash have been documented. This is only the tip of the iceberg, since most dumps are not monitored.[11] [Appendix 1 contains a list of the 137 contaminated sites in 35 states.]

In 2010, the EPA published a risk assessment that found extremely high risks to human health and the environment from the disposal of coal ash in waste ponds and landfills.[12] The chart below compares the EPA's findings on the cancer risk from arsenic in coal ash disposed in some unlined waste ponds to several other cancer risks, along with the highest level of cancer risk that the EPA finds acceptable under current regulatory goals.[13] The risk from coal ash is **2,000 times greater** than that regulatory goal.



Despite the high threat, as this report explains, most states fail to require basic measures to prevent the release of toxic chemicals from coal ash into our air, water supplies, lakes and streams. In fact, most states do not even require coal ash dumps to take measures to detect such releases.

PART II. EXPOSING STATE SECRETS

Grossly Inadequate State Programs

Missing Safeguards at Coal Ash Ponds and Landfills

Below is a damning indictment of the entire nation's state regulatory programs, revealing a widespread absence of basic safeguards across the U.S. Table 1 indicates how few states impose specific basic safety requirements that should be mandated in all states for all coal ash ponds and landfills.

Table 1. Failure of State Programs to Impose Basic Safeguards at Coal Ash Dumps

Regulatory Safeguard	States that Fail to Require Safeguard at All (new & existing) Ponds	States that fail to Require Safeguard at All (new & existing) Landfills	States that Fail to Require Safeguard at New Ponds	States that Fail to Require Safeguard at New Landfills
Groundwater Monitoring *during operation*	35 of 37 states 86% total coal ash*	33 of 37 states 95% total coal ash	35 of 37 states 86% total coal ash	29 of 37 states 83% total coal ash
Composite Liner	*No states have retroactive liner requirements*	*No states have retroactive liner requirements*	34 of 37 states 80% total coal ash	32 of 37 states 90% total coal ash
Leachate Collection System	*No states have retroactive leachate requirements*	*No states have retroactive leachate requirements*	31 states of 37 76% total coal ash	25 of 37 states 67% total coal ash
Daily Cover	*Not applicable*	30 of 37 states 72% total coal ash	*Not applicable*	30 of 37 states 72% total coal ash
Dust Controls	36 of 37 states 87% total coal ash	24 of 37 states 59% total coal ash	36 of 37 states 87% total coal ash	24 of 37 states 59% total coal ash
Run-off Controls	34 of 37 states 84% total coal ash	20 of 37 states 55% total coal ash	34 of 37 states 84% total coal ash	20 of 37 states 55% total coal ash
Separation from Water Table	*No states have retroactive siting requirements*	*No states have retroactive siting requirements*	31 of 37 states 74% total coal ash	22 of 37 states 64% total coal ash
Financial Assurance	25 of 37 states 64% total coal ash	19 of 37 states 50% total coal ash	25 of 37 states 64% total coal ash	18 of 37 states 48% total coal ash
Groundwater Monitoring (30 years after closure)	36 of 37 states 97% total ash	32 of 37 states 73% total coal ash	36 of 37 states 97% total coal ash	31 of 37 states 71% total coal ash
Inspection of Pond by State Regulators	24 of 37 states 57% total coal ash	*Not applicable*	24 of 37 states 57% total coal ash	*Not applicable*
Regular Reporting by Pond Operators	28 of 37 states 61% total coal ash	*Not applicable*	24 of 37 states 55% total coal ash	*Not applicable*
Emergency Action Plan for Coal Ash Ponds	19 of 37 states 44% total coal ash	*Not applicable*	18 of 37 states 43% total coal ash	*Not applicable*

*Percentage of total coal ash generated in the U.S. in 2005. Percentage indicates the portion of total coal ash that is not covered by the specific safeguard.

How does your state stack up? Table 2, below, lists the 37 states (comprising 98 percent of the ash generated in the U.S.) and the safeguards required by each state. The requirements in this table address both coal ash landfills and ponds. Appendix 2 of this report provides citations to all state regulatory requirements.

Table 2. State-by-State Failure to Impose Basic Safeguards at Coal Ash Dumps[14]

State	Require groundwater monitoring at all new and existing ponds	Require groundwater monitoring at all new and existing landfills	Require composite liners for all new ponds	Require composite liners for all new landfills	Prohibit ash ponds from being constructed in the water table	Prohibit coal ash landfills from being constructed in the water table	Require financial assurance for coal ash ponds	Require financial assurance for coal ash landfills
Alabama	No	No	No	Yes	No	Yes	No	Yes
Alaska								
Arizona	No	No	No	No	No	No	No	No
Arkansas								
California								
Colorado	No	No	No	No	Yes	Yes	Yes	Yes
Connecticut								
Delaware								
Florida	No	No	No	No	No	No	No	No
Georgia	No	No	No	No	No	No	Yes	Yes
Hawaii								
Idaho								
Illinois	No	Yes	No	No	No	Yes	Yes	Yes
Indiana	No	No	No	No	No	No	No	Yes
Iowa	No	No	No	No	No	Yes	No	Yes
Kansas	No	No	No	No	No	No	No	No
Kentucky	No	No	No	No	No	No	No	No
Louisiana	Yes	No	Yes	Yes	No	No	Yes	Yes
Maine								
Maryland	No	No	No	No	No	Yes	No	No
Massachusetts								
Michigan	No	No	No	No	No	Yes	Yes	Yes
Minnesota	No	No	No	No	No	Yes	No	No
Mississippi	No	No	No	No	No	No	No	No
Missouri	No	No	No	No	No	No	Yes	Yes
Montana	No	No	No	No	No	No	No	No
Nebraska								
Nevada	No	Yes	No	Yes	No	Yes	No	Yes
New Hampshire	No	Yes	No	No	No	Yes	Yes	Yes
New Jersey	No	Yes	No	No	No	Yes	No	Yes
New Mexico	No	No	No	No	No	No	No	No
New York	No	No	No	No	No	No	No	No
North Carolina	No	No	No	Yes	Yes	Yes	No	Yes
North Dakota	No	No	No	No	No	No	No	No
Ohio	No	No	No	No	No	No	No	No
Oklahoma	No	No	No	No	Yes	Yes	Yes	Yes
Oregon								
Pennsylvania	Yes	No	Yes	No	Yes	Yes	Yes	Yes
Rhode Island								
South Carolina	No	No	No	No	No	No	No	Yes
South Dakota	No	No	No	No	No	No	No	No
Tennessee	No	No	No	No	No	No	No	No
Texas	No	No	No	No	No	No	No	No
Utah	No	No	No	No	No	No	No	No
Vermont								
Virginia	No	No	No	No	No	No	No	No
Washington	No	No	No	No	No	No	No	No
West Virginia	No	No	Yes	No	Yes	Yes	Yes	Yes
Wisconsin	No	No	No	Yes	Yes	Yes	Yes	Yes
Wyoming	No	No	No	No	No	No	Yes	Yes

Gray indicates data not available

States that exempt on-site storage or allow for variance of safeguards per regulator discretion are classified as lacking the requirement.

*With respect to dry landfills, Tennessee law provides for groundwater monitoring, financial assurances, landfill siting and composite liners merely as a default. Tenn. Comp. R & Regs. 1200-01-07-.01 et. seq. The same law also contains a very broad provision to allow the Commissioner of the Tennessee Department of Environment and Conservation to waive any of these provisions at his discretion. Tenn. Comp. R & Regs. 1200-01-07-.01(5).

Missing Coal Ash Pond Safeguards

Because disposal of coal ash in ponds presents the additional threat of catastrophic failure, which can be deadly to nearby communities and cause significant economic and environmental destruction, basic requirements related to structural stability are presented separately. Table 3, below, presents the components of an adequate pond and dam safety program and indicates how many states fall short. Appendix 3 of this report provides the corresponding state regulatory citations.

Table 3. Essential Coal Ash Pond Safeguards Missing in State Regulatory Programs[15]

State	Requires Dam Design/Super-vision by an Engineer	Size Threshold for Regulation	Requires Frequent Visual Inspection By Operator	Geotechnical/ Engineering Inspections by Operator	Requires Regular Reporting (*construction period only)	Requires Inspection by Regulators	Requires Emergency Action Plan	Requires Inundation Mapping	Requires Certification of Construction	Requires Meeting Design Standards and Specifications	Bond	No. of Dams	No. of Dams Rated Significant or High Hazard	No. of Dams over 25 ft or 500 acre-feet	Percentage of Dams with Hazard Ratings	Number of Dams rated "Poor"	Percentage of Dams Inspected by Regulators in Last 5 years
Alabama	No	None	No	None	No	None	No	No	No	No	No	15	5	13	47%	3	0%
Alaska																	
Arizona	Yes	Large	Yes	1–5 yrs	Frequent*	None	Yes	Yes	Inspection‡	Yes	Yes	15	10	8	66%	0	66%
Arkansas																	
California																	
Colorado	Yes	Medium	Yes	Infrequent	Infrequent	None	Yes	Yes	Yes	Yes	Yes	40	0	1	15%	0	5%
Connecticut																	
Delaware																	
Florida	No	Large	No	None	None	None	No	No	No	No	No	9	0	1	89%	0	100%
Georgia	Yes	Very Large	Yes	For Permit	Only if Problem	None	No	No	No	Yes	No	29	9	19	34%	1	7%
Hawaii																	
Idaho																	
Illinois	Yes	Medium	Operation Plan†	For Permit	Frequent	None	Partial	No	Yes	Yes	Yes	38¶	2	16	24%	0	0%
Indiana	No	Very Large	No	None	None	1–5 yrs	No	No	No	Yes	No	71	4	26	6%	25	8%
Iowa	Yes	Medium	Annual	As Follow Up	Frequent	1–5 yrs	No	No	Inspection	Yes	Yes	43	0	3	0%	0	0%
Kansas	Yes	Large	No	3–5 yrs	Frequent*	None	Yes	Yes	Yes	Yes	No	13	1	5	8%	0	15%
Kentucky	Yes	Large	No	None	Infrequent	1–5 yrs	No	No	Yes	Yes	No	43	12	21	54%	0	28%
Louisiana	Yes	Large	Operation Plan	None	Only if Problem	None	Yes	Yes	No	Yes	No	11	0	8	0%	3	0%
Maine																	
Maryland	Yes	Small	No	None	Failure Only	None	Partial	No	Yes	Yes	No	0	0	0	100%	0	N/A
Massachusetts																	
Michigan	Yes	Small	No	3–5 yrs	Infrequent	None	Yes	Yes	Inspection	Yes	Yes	10	0	6	10%	0	90%
Minnesota	Yes	Large	Operation Plan	None	Infrequent	1–8 yrs	Partial	No	Yes	No	No	21	3	10	19%	2	19%
Mississippi	Yes	Medium	Yes	For Permit	Frequent	None	Yes	No	Yes	Yes	No	1	0	1	0%	0	100%
Missouri	No, if Permit	Very Large	Operation Plan	For Permit	Infrequent	None	Yes	No	Yes	Yes	No	32	0	15	0%	0	0%
Montana	Yes	Large	Operation Plan	5 yrs	Infrequent	None	Partial	Yes	Yes	Yes	Yes	9	3	2	100%	0	0%
Nebraska																	
Nevada	No	Medium	No	None	None	None	No	No	No	No	No	8	8	0	100%	0	0%
New Hampshire	Yes	Small	Operation Plan	None	Infrequent	1–5 yrs	Yes	Yes	Yes	Yes	No	0	0	0	100%	0	N/A
New Jersey	Yes	Small	No	1–10 yrs	Frequent*	None	Yes	Yes	Yes	Yes	No	0	0	0	100%	0	N/A
New Mexico	Yes	Large	Operation Plan	5 yrs	Infrequent	None	Yes	Yes	Yes	Yes	No	8	3	2	50%	0	0%
New York	No	None	No	None	No	None	No	No	No	No	No	6	0	0	0%	0	100%
North Carolina	Yes	Medium	Operation Plan	None	Infrequent	1–5 yrs	No	No	Yes	Yes	No	26	18	26	100%	6	19%
North Dakota	Most	Large	Operation Plan	None	Frequent	None	No	No	Yes	No	Yes	16	0	4	31%	0	6%
Ohio	Yes	Medium	Operation Plan	5 yrs	Frequent	5 yrs, at least	Yes	Yes	Yes	Yes	Yes	29	17	22	72%	10	66%
Oklahoma	Yes	Large	No	1–5 yrs	Infrequent	1–5 yrs	Yes	Yes	Yes	Yes	No	5	0	3	0%	0	100%
Oregon																	
Pennsylvania	Yes	Large	Yes	Annual	Frequent	None	Yes	No	Yes	No	Yes	31	5	7	39%	1	61%
Rhode Island																	
South Carolina	Yes	Large	Operation Plan	None	Frequent*	None	Yes	Yes	Yes	Yes	No	22	0	13	4%	0	0%
South Dakota	Yes	Large	No	None	None	1–5 yrs	Partial	No	Yes	Yes	No	0	0	0	100%	0	N/A
Tennessee	No	None	No	None	No	No	No	No	No	No	No	18	14	16	83%	8	0%
Texas	Yes	Large	Operation Plan	Annual	Frequent	5 yrs for some	Yes	No	Yes	Yes	No	31	0	6	0%	3	26%
Utah	Yes	Medium	Operation Plan	None	Frequent	5 yrs for some	Yes	Yes	Inspection	Yes	No	6	0	4	83%	0	0%
Vermont																	
Virginia	Yes	Large	Operation Plan	Annual	Infrequent	None	Yes	Yes	Yes	Yes	No	11	2	9	73%	1	36%
Washington	Yes	Medium	Operation Plan	Annual	Frequent	1–5 yrs	Yes	Yes	Yes	Yes	No	0	0	0	100%	0	N/A
West Virginia	Yes	Large	Yes	1–7 yrs	Infrequent	None	Yes	Yes	Yes	Yes	No	12	10	9	83%	0	83%
Wisconsin	No	None	No	None	No	None	No	No	No	No	No	18	0	0	0%	0	6%
Wyoming	Yes	Small	No	None	Infrequent	Every 5+ yrs	No	No	No	No	No	17	3	9	41%	0	18%

† Requires aapproved operation and monitoring plan but regs do not specify a schedule ‡ Requires a post-construction inspection ¶ 38 dams reflects US EPA survey; according to Illinois EPA, there are 83 coal ash ponds in Illinois

Colors	Good	Needs Improvement	Poor	Bad or Absent	Data Unavailable

Inconsistency Breeds Endangerment

State regulations governing coal ash are often wildly inconsistent with each other as well as internally inconsistent. These inconsistencies lead to the unequal protection of American communities from toxic waste. Fairness requires that federal waste regulations establish a floor of mandatory safeguards to ensure that all citizens, no matter where they live, are protected from coal ash.

Inconsistent state regulations lead to **cross-border dumping**. For example, lack of regulations in Alabama has made that state a coal-ash dumping ground. In fact, the Arrowhead landfill in Perry County, Alabama, which has received about 5 million tons of coal ash from Tennessee since 2009, is licensed to receive ash from no less that 33 states.[16] Inconsistent state regulations also result in **environmental injustice**-- the states with the most lax coal ash regulations are the states where coal ash dumps are most likely to disproportionately impact low-income communities and communities of color.

Internally, states also leave their citizens unprotected. For example, Wisconsin's regulation of wet ash disposal lacks many of the protections afforded to dry disposal in the state. Despite the existence of 18 coal-ash impoundments in Wisconsin, these dams are not included within the scope of the state's dam safety program.[17] This means that there are no structural safety or dam integrity regulations applying to coal-ash dams in the state. Likewise state regulators do not monitor the construction or operation of Wisconsin coal-ash dams. As a result, state regulators have inspected only one of the state's 18 dams within the last five years.

In the case of Florida, your protection from dangerous coal ash ponds depends on where you live within the state. Florida is a complex patchwork of local rules promulgated by five individual water management districts.[18] While three of these districts require a professional engineer to design or certify plans for a new dam, two have no such requirement.[19] Only one district requires regular inspections by regulators, and none of the districts require emergency action plans to protect human life during a disaster.[20] While the state of Florida does require permits for dams constructed within the state, the terms of those permits are left up to the individual water management districts.[21] The result of all of this—you should feel much safer living next to a dam in Florida Northwest than along the Suwanee River.

The only way to cure these inconsistencies is for EPA to establish mandatory federal regulations under RCRA that apply equally in all states. This is a national problem that demands a national solution.

PART III.

The 12 Most Dangerous States

The 12 states described below make up about 50 percent of the yearly generation of coal ash—in total, 70.6 million tons of coal ash each year are generated in these states.[22] Together the 12 states host at least 217 coal-fired power plants.[23] All of these states dispose of a substantial amount of their waste in over 350 coal ash ponds, the most dangerous type of coal ash disposal.[24] **In general, the weakest state programs are found in the states that produce the largest quantities of toxic waste and employ wet disposal, the most dangerous method of disposal.**

Below are brief descriptions of the 12 most dangerous states.[25] Unless otherwise noted, the source for information for the number, age and size of coal ash ponds is EPA's Database of Survey Responses from the Agency's 2009–2011 "Information Request Responses from Electric Utilities."[26] The source for information for the condition of coal ash dams and ponds is EPA's "Coal Combustion Residuals Impoundment Assessment Reports," including the contractor reports assessing the structural integrity of numerous coal ash impoundments.[27]

NATIONAL INVENTORY OF DAMS CRITERIA: "HIGH," "SIGNIFICANT," AND "LOW"[1]
The hazard potential ratings refer to the potential for loss of life or damage if there is a dam failure.

- **High Hazard Potential:** Dams assigned the high hazard potential classification are those where failure or mis-operation will probably cause loss of human life.
- **Significant Hazard Potential:** Dams assigned the significant hazard potential classification are those dams where failure or mis-operation results in no probable loss of human life, but can cause economic loss, environment damage, disruption of lifeline facilities, or impact other concerns.
- **Low Hazard Potential:** Dams assigned the low hazard potential classification are those where failure or mis-operation results in no probable loss of human life and low economic and/or environmental losses.

1. Alabama

Coal ash Generation: 3,210,337 tons annually[28]
Rank for Coal Ash Generation in US: 14th
Number of Ash Ponds: 15
Number of Documented Sites Contaminated by Coal Ash: 2

Alabama represents the worst of the worst when it comes to coal-ash disposal. First, Alabama has **no** laws or regulations on the books to specifically ensure the safety of the state's coal ash dams. It is the only state in the country without such laws. Because there are no federal laws to ensure dam safety, this essentially means that Alabama dams are **completely unregulated**. Until 2011, Alabama also completely exempted coal ash disposal in landfills. Consequently, coal ash from its ten coal-fired plants has been dumped mostly in unlined, unregulated, and unmonitored ponds and landfills. Given the historical absence of controls on coal ash disposal, it is outrageous that more than 5 million tons of ash from the Kingston TVA spill was shipped to Alabama for disposal.[29]

State oversight of Alabama's dangerous dams is also totally missing. None of the state's 15 coal ash dams have been subject to state regulatory inspections in the past five years. After inspections by the EPA and TVA contractors in 2009–2010, five of the dams were given poor ratings and two had to make immediate repairs to improve stability. Alabama dams are, on average, the tallest and largest coal ash dams in the 12 most dangerous states. The average height is nearly 7 stories tall (over 66 feet), and the average surface area is greater than 192 acres (about 151 football fields)—more than twice the average of coal ash ponds in the other nine states. These large ponds pose high threats—two of Alabama's dams are high hazard, and 11 are significant hazard dams. Lastly, these ponds are **old**—the average age of an Alabama coal ash pond is 40 years. According to the EPA, that's the estimated lifespan, but Alabama utilities have announced no retirement plans.[30]

Alabama's coal ash ponds disproportionately impact low-income communities and communities of color. The EPA statistics show that more than 40 percent of the citizens living near coal ash ponds in Alabama are non-white. Also, about 25 percent of nearby residents are below the poverty line, which is more than twice the national average poverty rate of 11.9 percent.

2. Georgia

Coal ash Generation: 6,077,700 tons annually
Rank for Coal Ash Generation in US: 8th
Number of Ash Ponds: 29
Number of Documented Sites Contaminated by Coal Ash: 1

Georgia is the eighth largest coal ash-producing state, and, in gross disregard to the safety of its citizens, it has a hands-off approach to coal ash at its 29 coal ash ponds. Georgia's role in ensuring the safety of coal ash impoundments basically stops at dam construction. There is

nothing in Georgia law to specify how often inspections must occur, and in practice, regulatory inspections of Georgia's numerous aging ponds are exceedingly rare—only 7 percent of Georgia's dams have been inspected by the state in the past five years, yet 13 of the state's 29 ponds are at least 40 years old. Georgia requires no emergency action plans, no inundation maps to determine what areas would be impacted in the event of a breach, and no bonds to cover closure or cleanup.

The threat from coal ash in Georgia is substantial. The state ranks second among the 12 most dangerous states in total surface area covered by impoundments (2,218 acres—almost three times the size of Central Park). Yet the state does not require liners or monitoring wells at coal ash ponds—despite the fact that many of the ponds are built on unstable, karst terrain.[31] The state does not even prohibit the siting of landfills and ponds directly in the water table. Of Georgia's 29 coal ash ponds, two are rated high hazard and 11 are rated significant hazard. So far, Georgia has one dam rated poor by EPA inspectors—the 25-year-old, 54-acre ash pond at Georgia Pacific's Plant Hammond in Coosa, GA, where the percent of citizens living below the poverty line exceeds the county average.

3. Illinois

Coal ash Generation: 3,856,748 tons annually
Rank for Coal Ash Generation in US: 11th
Number of Ash Ponds: 83
Number of Documented Sites Contaminated by Coal Ash: 12

State regulatory control of Illinois' many large coal ash ponds is sorely missing, and the threat to Illinois citizens is substantial. The state has 68 operating coal ash dams and 15 ponds that no longer accept waste, but which still pose a danger to adjacent communities.[32] In fact, counting these retired ponds, Illinois ranks first in the nation in the number of coal ash ponds with 83. Even without including the 15 retired ponds, Illinois ranks second among the 12 most dangerous states in total surface area for its coal ash impoundments (over 3.3 square miles of ponded ash, which is more than 86 times the size of Chicago's famed Millennium Park). A recent inventory by the Illinois Environmental Protection Agency (IEPA) revealed that only about a third of Illinois ponds are lined or monitored.[33] This is no surprise because Illinois regulations do not require composite liners or groundwater monitoring at every coal ash pond and landfill. According to a 2010 assessment by the IEPA, 10 Illinois power plants with active ponds were characterized as having "high" to "very high" potential to contaminate a drinking water source. According to the U.S. EPA[34] and the IEPA,[35] coal ash has already contaminated water at 15 power plant sites in the state.

Disturbingly, the structural integrity of Illinois coal ash ponds remains unknown. Because there is no regular inspection requirement of ponds by state regulators, few of the state's 68 operating dams have been inspected by the state in the past five years. The EPA has inspected only four of the state's dams. In addition, only 10 of Illinois' ponds have been assigned hazard ratings, yet at least seven of the unrated ponds are taller than 25 feet.[36] Compounding Illinois'

problem is the lack of a requirement for area inundation maps—a key component of proper emergency planning because an inundation map indicates the area of probable flooding in the event of a dam failure. This is an environmental justice issue in Illinois, where approximately one-fifth of residents living near coal ash ponds are below the poverty line.

4. Indiana

Coal ash Generation: 8,798,844 tons annually
Rank for Coal Ash Generation in US: 6th
Number of Ash Ponds: 71
Number of Documented Sites Contaminated by Coal Ash: 9

Indiana citizens have good reason to worry about coal ash. Indiana is sixth in the nation in coal ash generation, and it has more operating coal ash ponds (71) than any other state in the U.S.[37] The state also has an alarmingly poor record of dam safety and water contamination and exceedingly lax regulations, even when compared to the other eleven most dangerous states. For example, in Indiana:

- A staggering 25 of the 41 coal ash dams inspected by the EPA to date were given a "poor" rating for structural integrity;
- There have already been two major 30 million gallon spills from coal ash ponds at the Eagle Valley Generating Station in Indianapolis and two spills at the R.M. Shafer Power Station;
- Contaminated groundwater has been documented at eight sites, including in the Town of Pines, which has been designated a Superfund site;[38]
- Only 11 percent of the state's ponds have had state regulatory inspections in the past five years; and
- Less than half of the state's coal ash dams have hazard ratings.

State regulations could hardly be worse. First, there are shockingly few requirements for ensuring dam safety in Indiana, including no requirement that the dam be designed by a professional engineer, no requirement to inspect dams, no reporting requirements, no inundation mapping, no emergency plans required, and no bond requirements.

Similarly, state law fails to protect drinking water and surface water from the leaching of toxic chemicals from ash. Indiana regulations do not require groundwater monitoring or composite liners at all ponds and landfills, nor do the regulations prohibit dumping directly into the water table. In fact, state regulators are clear in their opposition to such common-sense protections. In 2010, the Commissioner of the Indiana Department of Environmental Management denied that coal ash shares the "harmful characteristics" of other types of hazardous waste, and he urged EPA to weaken its proposed subtitle D standards to allow coal ash to be placed below the water table.[39] The eight contaminated sites in Indiana, including the poisoning of an entire town's drinking water aquifer, the large ash pond spills, and the 25 ponds with "poor" ratings are the direct result of the state's lax oversight.

5. Kentucky

Coal ash Generation: 9,197,567 tons annually
Rank for Coal Ash Generation in US: 5th
Number of Ash Ponds: 43
Number of Documented Sites Contaminated by Coal Ash: 4

Kentucky is on the most dangerous list because the threat from coal ash is enormous in this leading coal-burning state; yet state regulations require exceedingly little from owners and operators of coal ash ponds and landfills. Kentucky is fifth in the nation in coal ash generation, and it has 43 operating coal ash ponds—21 of which exceed a height of 25 feet or impound more than 500 acre-feet of ash. In fact, Kentucky has the third largest coal ash storage capacity (more than 64,000 acre-feet) in the nation. This is equivalent to covering the Churchill Downs Racetrack, home to the Kentucky Derby, is held each year, under 800 feet of toxic sludge. Kentucky ties Ohio for the most high hazard dams (eight). It should concern Kentucky residents that professional engineers did not design 20 of the state's 43 dams nor did they construct 27 of them. Only 15 of Kentucky's dams have been inspected by the EPA to date, and, by admission of the power plant owners, engineers do not presently monitor 30 of the 43 dams.

State oversight of the coal ash dams is also minimal. There are no regular reporting requirements after construction, except for certificate renewal every five years. Operators are not given an inspection frequency and are not required to post a bond to ensure safe operation and maintenance or even completion of dam construction. Finally, Kentucky does not require emergency action planning or inundation mapping, which is astounding given the presence of eight high hazard dams that are likely to take human lives if they break and six significant hazard dams that would cause substantial economic and/or environmental damage in the event of failure.

Groundwater contamination from coal ash dumping has been documented at four sites in Kentucky. Many more sites are likely contaminated but not detected, because the state does not require composite liners at all ponds and landfills nor does the state prohibit dumping directly into the water table. Yet because Kentucky regulations do not require groundwater monitoring at all coal ash dump sites, the extent of the contamination is largely unknown. We do know, however, that by the EPA's calculation, **100 percent** of the toxic chemical releases to land of arsenic, chromium and mercury in Kentucky come from disposal of coal ash in landfills and ponds.[40]

6. Missouri

Coal ash Generation: 2,679,742 tons annually
Rank for Coal Ash Generation in US: 16th
Number of Ash Ponds: 32
Number of Documented Sites Contaminated by Coal Ash: 4

In Missouri, only the largest, most dangerous of the state's 32 coal ash ponds are regulated for dam safety. Amazingly, Missouri allows ponds impounding more than 170 million gallons of coal ash to escape safety regulations. This amount is roughly equivalent to 35,000 bathtubs full of coal ash or an area the size of Washington's National Mall covered in sludge about two feet deep. Furthermore, Missouri has not assigned a hazard rating to a single coal ash impoundment in the state. The EPA has inspected only two of Missouri's 32 dams and rated those dams as high hazard and significant hazard. Undoubtedly, many of Missouri's other ponds are also potentially dangerous because 14 ponds are over 25 feet high or impound more than 500 acre-feet. Yet state regulators have inspected only one dam in the past five years, despite the fact that about half the dams were not constructed by professional engineers and fewer than half are currently monitored by one.

Other key safety regulations to protect the public are also missing in Missouri. State regulations do not require regular inspections by dam safety officials. Missouri regulations also do not require groundwater monitoring or composite liners at all ponds and landfills, nor do the regulations prohibit dumping directly into the water table or require bonds to ensure cleanup at coal ash landfills.

These deficiencies are threatening Missouri's environment. The Missouri Department of Natural Resources (DNR) has known since 1992 that a 154-acre, unlined ash pond at Ameren's Labadie plant – the largest coal plant in the state and the 14th largest coal plant in the nation – has been leaking some 50,000 gallons per day. DNR has not required groundwater monitoring or cleanup, despite the threat to the local population that relies on groundwater for drinking water and agricultural use. DNR has also allowed the plant to continue operating under a 1994 NPDES permit, which technically expired in 1999, without issuing an updated renewal permit to require groundwater monitoring and cleanup. Missouri citizens deserve better.

7. North Carolina

Coal ash Generation: 5,504,531 tons annually
Rank for Coal Ash Generation in US: 9th
Number of Ash Ponds: 26
Number of Documented Sites Contaminated by Coal Ash: 10

Every single one of the North Carolina's 26 coal ash dams is enormous. The average dam height in North Carolina is more than six stories tall (62 feet), and the total storage capacity is nearly 65,000 acre-feet—enough toxic waste to flood an area nine times the size of Central Park one foot deep. This means that it is essential that North Carolina have strict regulations for dam safety. Unfortunately, the state does not require operators to submit regular reports to regulators, have emergency action plans, generate inundation maps, or post bonds in the case of dam failure.

Only 19 percent of North Carolina's ponds have been inspected by a state regulator in the past five years. Over the last two years, however, the EPA inspected 22 of North Carolina's dams and

gave six of the ponds a poor rating. One of these high hazard poor-rated dams, at Progress Energy's Asheville Electric Plant, is located in a densely populated area with nearly 1,800 residents within a one-mile radius. The population near the plant also exceeds state averages for low income and minority residents.

North Carolina also does not require groundwater monitoring nor composite liners at all its ash ponds. North Carolina's lax regulation of coal ash ponds and landfills has resulted in 10 dump sites where local communities are threatened because groundwater or surface water has been contaminated with toxic pollutants such as arsenic, selenium and boron.[41]

8. Ohio

Coal ash Generation: 10,429,446 tons annually
Rank for Coal Ash Generation in US: 3rd
Number of Ash Ponds: 29
Number of Documented Sites Contaminated by Coal Ash: 7

Despite the fact that Ohio is the third largest producer of coal ash in the U.S., Ohio has one of the most lax regulatory programs in the nation. Ohio excludes all coal ash from regulation by classifying it as "nontoxic."[42] Due to lax state regulations, which fail to require composite liners at all coal ash ponds and landfills, water contamination has occurred at seven coal ash dump sites across the state. Many other sites in Ohio may also be poisoned but remain undetected, because the state does not require groundwater monitoring at all sites.

We do know, however, that something has gone terribly wrong at Ohio's huge coal ash ponds. The EPA gave a poor rating to 10 Ohio dams, greater than a third of Ohio's 29 coal ash dams. Three poorly-rated dams at Dayton Power and Light's J.M. Stuart Station in Aberdeen are located in the most densely populated area of any of the 55 dams in the U.S. found by the EPA to be in poor condition. The J. M. Stuart dams have 2,265 residents within a 1-mile radius. The population near the Stuart Station also exceeds state averages for low income and minority populations.

Ohio citizens have great reason to be concerned. The average dam height in Ohio is more than five stories tall (52.6 feet), and the total storage capacity is the third largest of the 12 worst states (over 73,000 acre-feet)—enough to flood 114 square miles in sludge a foot deep. Sixteen (over half) of Ohio's ponds have dams that are rated either high or significant hazard. Ohio likely has more high and significant hazard dams, since five not-yet-rated dams are over 25-feet high (with four over 40-feet high). Nine of Ohio's 29 dams were not designed by a professional engineer, and 10 of the state's dams were not constructed by one. The state also has some of the oldest dams of the 12 states. The average age of Ohio coal ash dams is 39 years.

9. South Carolina

Coal ash Generation: 2, 178, 359 tons annually
Rank for Coal Ash Generation in US: 21st
Number of Ash Ponds: 22
Number of Documented Sites Contaminated by Coal Ash: 4

A striking proportion of the 22 ash dams in South Carolina – over 50% -- are large capacity impoundments or have dam heights above 25 feet. Despite the fact that the breach of any of these dams would undoubtedly inundate a large area, the state does not require hazard ratings. Recent inspections by EPA contractors discovered that six of the state's unrated dams are "significant hazard."[43] Compounding this problem, the state does not require **any** state regulatory inspections and **none** of the dams in South Carolina have been subject to a state regulatory inspection within the past five years. While South Carolina has a fair set of regulations for the design and construction of new dams, its laws are deficient when it comes to inspection and oversight of existing dams. Annual geotechnical inspections should be required of the operators, and experienced regulators need to take a more active oversight role. With so many large dams in the state, it is imperative that regulators beef up both the contents and application of dam safety regulations – it is the only way to minimize the threat to the environment and people of South Carolina.

To date, there is evidence that at least five coal ash dump sites in South Carolina have contaminated groundwater or surface water with arsenic and other dangerous chemicals. In fact, one of the polluted and most thoroughly studied cases of coal ash contamination is in the Savannah River in South Carolina. A power plant discharged coal ash into ponds that overflowed into the Savannah River floodplain for more than a decade. Scientists found severe ecological damage, especially to amphibians, which have experienced mutations and die-offs.[44] Concentrations of arsenic, selenium, and strontium in some amphibians were as much as 11-35 times higher than in the same species collected from unpolluted wetlands. Arsenic was also found leaking from ponds at the SCE &C Wateree Station, SCE&G Urquhart Station and the SC Public Service Authority's Grainger Station.[45] At the Grainger Station, arsenic was found up to 91 times the drinking water standard in groundwater near the Waccamaw River. These releases are not surprising since South Carolina regulations do not require composite liners for their ponds and landfills.

10. Tennessee

Coal ash Generation: 3,240,120 tons annually
Rank for Coal Ash Generation in US: 13th
Number of Ash Ponds: 18
Number of Documented Sites Contaminated by Coal Ash: 7

In 2008, the cataclysmic TVA disaster graphically demonstrated just how dangerous it is to live next to a coal ash pond. The collapse of a dam at TVA's Kingston Fossil Plant destroyed a riverside community, and the decade-long cleanup is estimated to cost more than $1 billion.

The disaster in Harriman, Tennessee spurred TVA to evaluate its other large coal ash dams (24 in total) in TVA's three-state region. At TVA's seven Tennessee plants, inspectors found that half the ponds (eight) failed to meet federal stability standards established by the U.S. Army Corps of Engineers.[46] Remedial action was required at all eight dams to increase stability.

The collapse of the Kingston dam was a direct result of the absence of state oversight and maintenance at Tennessee's coal ash dams. There is **no set of rules that apply to the structural stability and safety of Tennessee's coal ash dams.** While the state does have a comprehensive set of dam safety laws and regulations, **it specifically exempts coal-ash dams from its scope.** While this would be shocking in any state, it is abhorrent in Tennessee, which suffered the worst coal-ash disaster, and arguably one of the worst environmental disasters in history. Given the absence of state regulations, it is not surprising that prior to the dam failure, none of the dams in Tennessee had been subject to an official regulatory inspection within the previous five years.

Similarly, Tennessee regulations fail to prevent contamination of water via the slow escape of chemicals from landfills and impoundments. With respect to dry landfills, Tennessee law provides for groundwater monitoring, financial assurances, landfill siting and composite liners merely as a default.[47] The same law also contains a very broad provision to allow the Commissioner of the Tennessee Department of Environment and Conservation to waive any of these provisions at his discretion.[48] Eight sites in the state have been documented with contamination of surface and/or groundwater from coal ash. One of the most polluted is the Superfund site at the Oak Ridge Y-12 Plant where arsenic and selenium releases led to fish deformities and a widespread extirpation of aquatic life.[49]

11. Texas

Coal ash Generation: 13,165,728 tons annually
Rank for Coal Ash Generation in US: 2nd
Number of Ash Ponds: 31
Number of Documented Sites Contaminated by Coal Ash: 5

Texas is the second largest generator of coal ash in the U.S., but the laws in Texas governing the disposal of ash are among the worst. Texas excludes from regulation all coal ash that is disposed of "on-site," which is defined in Texas as anywhere within 50 miles of the power plant![50] Texas also excludes from regulation all coal ash that is destined for "beneficial" reuse.[51] This is a big problem because in Texas "beneficial" reuse includes minefilling—the dumping of industrial waste in active and abandoned coal mines. This type of dumping often occurs directly into aquifers and has resulted in significant contamination in several states.[52]

The harmful release of pollutants to water and air from landfills is highly likely, because at least seven Texas coal plants employ *no* liners or dust controls at their landfills.[53] In fact, dangerous contamination of drinking water is occurring at the Lower Colorado River Authority, Fayette Power Project in La Grange, where coal ash is polluting groundwater with arsenic, molybdenum

and selenium exceeding state standards-- which has required the Texas Commission on Environmental Quality to warn neighboring landowners.[54]

There is also abundant evidence of dangerous chemical releases from coal ash ponds in Texas. Texas coal ash ponds are not especially large or high, but they are numerous (31). Discharges from coal ash ponds caused the contamination of at least three reservoirs with selenium- the Brandy Branch Reservoir in northeastern Texas along the Louisiana border, the Welsh Reservoir northeast of Dallas, and the Martin Lake Reservoir southeast of Dallas. Coal ash discharges poisoned the water, caused major fish kills, and contaminated fish with high levels of selenium that lasted for over a decade. And the harm was not limited to fish. The contaminated fish threatened the health of those who fished and consumed them. In response, the Texas Department of Health issued fish consumption advisories, in one case warning people to eat no more than eight ounces of fish from the reservoir per week. Another advisory urged children under six and women who were pregnant or might become pregnant not to consume any fish from the reservoir whatsoever. That advisory remained in effect for 12 years.[55] In addition, there is evidence that the toxin entered the food chain resulting in elevated selenium concentrations in birds nesting near the lakes. Even now, decades after the releases occurred, selenium concentrations in fish remain as high as 1.8 to 27 times the national average in two of the three reservoirs, according to 2009 Health Consultation by the Agency for Toxic Substances and Disease Registry.[56]

Lastly, the legacy of poor regulatory authority in Texas was evident in the determination in March 2011 by U.S. EPA that three coal ash ponds were in "poor" condition.[57] Among the problems observed were erosion, seeps and the absence of engineering studies that indicate the structural stability of the ponds. EPA also noted that the absence of documented inspections and emergency action plans.

12. Virginia

Coal ash Generation: 2,388, 527 tons annually
Rank for Coal Ash Generation in US: 18th
Number of Ash Ponds: 11
Number of Documented Sites Contaminated by Coal Ash: 4

Coal ash from Virginia's 16 coal-fired power plants has created a substantial toxic legacy in the Commonwealth. Coal ash contamination has generated at least two federal Superfund sites in Virginia,[58] including one on the National Priority List of the nation's most contaminated Superfund sites,[59] as well as two other sites where coal ash contaminated groundwater[60] or caused extensive ecological damage.[61] Despite the history of coal ash contamination, Virginia regulations do not require composite liners, groundwater monitoring and daily cover at every coal ash pond and landfill.

The legacy of mismanagement extends to oversight of the structural integrity of Virginia's large coal ash ponds, as well. Virginia's coal ash dams are some of the oldest, having an average age

of 40 years. Virginia has 11 ash ponds, including five significant hazard coal ash dams, with an average height of more than five stories. The EPA gave one of Virginia's significant hazard dams a poor rating and asked the owner, Dominion Virginia Power, to take immediate remedial action at the Chesapeake Energy Center to address the "urgent action items" that "require immediate attention to ensure the structural integrity of the impoundment in the near term."[62] Serious problems like these may well escape detection in Virginia because the Commonwealth does not require inspection of dams by state regulators and requires only infrequent reporting by owners. Virginia also does not require a bond to ensure safe operation and maintenance or even completion of dam construction.

But Virginia's lack of regulatory control over coal ash is playing with fire. One hundred percent of the releases to land of arsenic, chromium and selenium, and over 92 percent of the releases to land of mercury, come from coal ash alone.[63]

[DIS]HONORABLE MENTION
The Wild West: Arizona, Montana, New Mexico, And Utah

Not only is the situation dismal in the 12 worst states, but some of the largest coal ash-generating states in the country have no or nearly no coal ash regulatory programs—and many are found in the arid west, where water is scarce. Two states—New Mexico and Utah[1]—exempt coal ash completely from regulation as a solid waste, leaving the disposal of coal ash virtually unregulated. Montana and Arizona are not much better. In these four arid states, with scarce and valuable underground sources of drinking water, very few safeguards are required.

CONCLUSION
The Myth is Busted

States Are Not Doing A "Good Job"

Clearly, federal coal ash regulations are needed to protect communities from leaking and unstable landfills and ponds. The states have had decades to get this right—but most states still have huge and dangerous gaps in their programs. The 37 state programs we examined, which cover 98 percent of all ash generated in the nation, largely fail to protect their citizens' drinking water, air and environment from some of the most toxic chemicals known to man. The lack of adequate state regulatory programs is a major rationale for a strong federal rule under subtitle C. Not only would a subtitle C rule set mandatory minimum national standards for all states to enforce, it would also provide the EPA with authority to enforce such regulations if states are

unable or unwilling to do so. Poisoned water, foul air and falling dams are not the inevitable consequences of coal ash disposal. These are threats that can and must be minimized by regulatory standards that require reasonable safeguards be followed. The states have failed miserably at this straightforward task and have placed the nation's most vulnerable communities at great risk. There is a solution, and the EPA proposed it over a year ago—regulation of coal ash as a hazardous waste under subtitle C of RCRA.

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[1] 75 Fed. Reg. 35,128, 35,157 (June 21,2010).

[2] U.S. Environmental Protection Agency, Regulatory Impact Analysis For EPA's Proposed RCRA Regulation of Coal Combustion Residues (CCR) Generated by the Electric Utility Industry, April 30, 2010 at page 124.

[3] 75 Fed. Reg. at 35,237.

[4] 75 Fed. Reg. at 35,238.

[5] IPL, Response to US EPA 104(e) Information Request to Indianapolis Power and Light Company- Eagle Valley Generating Station (May 13, 2009), available at http://www.epa.gov/osw/nonhaz/industrial/special/fossil/surveys/index.htm.

[6] *Id.*

[7] http://www.timesfreepress.com/news/2009/jan/13/tennessee-widows-creek-ash-may-be-more-toxic-kings/.

[8] http://www.starnewsonline.com/article/20100928/ARTICLES/100929663/1177?Title=Deluge-takes-toll-on-roads-ash-pond-sewers.

[9] US EPA, Human and Ecological Risk Assessment of Coal Combustion Wastes (April 2010) (draft).

[10] *Id.*

[11] Physicians for Social Responsibility, Coal Ash the Toxic Threat to Our Health and Environment (August 2010), http://www.psr.org/resources/coal-ash-the-toxic-threat-to-our-health-and-environment.html.

[12] *Id*.

[13] *Supra* at note iii. Date for cigarettes comes from Center for Disease Control, Cigarette Smoking-Attributable Morbidity-U.S. 2000, MMWR Weekly, September 5, 2003 / 52(35); 842–44.

[14] An appendix to Table 2 can be found at http://earthjustice.org/documents/report/pdf/state-groundwater-monitoring-requirements-coal-combustion-waste-landfills.

[15] The source for information in Table 3 concerning the number, size, hazard ranking, and inspection frequency of dams is EPA's May 2011 coal ash impoundment survey, available at http://www.epa.gov/osw/nonhaz/industrial/special/fossil/surveys/index.htm. EPA is in the process of inspecting dams, and new information, including newly-assigned hazard rankings, is posted by EPA at http://www.epa.gov/osw/nonhaz/industrial/special/fossil/surveys2/index.htm. The information in Table 3 reflects the data submitted to EPA by the dam owner/operators. It does not reflect the findings of EPA's inspections, which may both differ from and augment the industry-supplied information.

[16] http://adem.alabama.gov/newsEvents/notices/jun11/6perry.htm. The Arrowhead landfills is permitted to accept waste from Alabama, Arkansas, Connecticut, Delaware, Florida, Georgia, Illinois, Indiana, Iowa, Kentucky, Louisiana, Maine, Maryland, Massachusetts, Michigan, Minnesota, Mississippi, Missouri, New Hampshire, New Jersey, New York, North Carolina, Ohio, Oklahoma, Pennsylvania, Rhode Island, South Carolina, Tennessee, Texas, Vermont, Virginia, West Virginia, and Wisconsin. See also, http://perryherald.blogspot.com/2009/06/three-million-tons-of-coal-ash-headed.html.

[17] *See* Wisconsin Admin. Code NR § 333.03. This regulation defines a "dam" as "any artificial barrier in or across a water-course which has the primary purpose of impounding or diverting water." Because coal-ash impoundments do not fit within this regulatory definition of a "dam" they are not regulated by the Wisconsin dam safety program.

[18] http://www.dep.state.fl.us/water/mines/damsafe.htm. The Florida Dam Safety Program homepage describes the relationship between the Florida Department of Environmental Protection, the five regional water management districts and the U.S. Army Corps of Engineers.

[19] The districts of Northwest Florida, Florida Southwest, and South Florida all have such a design requirement. *See* Fla. Admin. Code §§ 40A-4.101 (Northwest Florida), 4OD-4.381(m) (Florida Southwest); *see also* Rules of the South

Florida Water Management District Appx. 6 Rule 1.3 *available at* http://www.dep.state.fl.us/water/mines/docs/BOR_08_00.pdf. The St. John's River and Suwanee River districts do not.

[20] The Northwest Florida Water Management district has an annual inspection requirement. *See* Fla. Admin Code § 40A-4.461. The state code contains only a vague "periodic inspection" requirement, which is not elaborated upon in any other district. Fla. Stat. § 373.423.

[21] A copy of each district's regulations are available at: http://www.dep.state.fl.us/water/mines/damsafe.htm.

[22] Based on 2005 coal ash generation volumes. *See* U.S. Environmental Protection Agency, Regulatory Impact Analysis For EPA's Proposed RCRA Regulation of Coal Combustion Residues (CCR) Generated by the Electric Utility Industry, 32 (April 30, 2010).

[23] *Id.*

[24] *Id.*

[25] Fact sheets on all listed states can be found at http://earthjustice.org/features/campaigns/state-fact-sheets-on-coal-ash.

[26] http://www.epa.gov/osw/nonhaz/industrial/special/fossil/surveys/index.htm.

[27] *See* http://www.epa.gov/osw/nonhaz/industrial/special/fossil/surveys2/index.htm.

[28] Information regarding amount of coal ash generated is EPA's Regulatory Impact Analysis for EPA's Proposed RCRA Regulation of Coal Combustion Residues (CCR) Generated by the Electric Utility Industry, specifically the 2007 US Department of Energy, Energy Information Agency (EIA) database for electricity power plants from the Form EIA-860 "Annual Electric Generator Report."

[29] US EPA, Database of Survey Responses, Information Requests from Electric Utilities, http://www.epa.gov/osw/nonhaz/industrial/special/fossil/surveys/survey5-16-11.pdf.

[30] 75 Fed. Reg. 35,153. EPA stated in the preamble to its proposed coal ash rule, "Surface impoundments are generally designed to last the typical operating life of coal-fired boilers, on the order of 40 years. However, many impoundments are aging: 56 units are older than 50 years, 96 are older than 40 years, and 340 are between 26 and 40 years old. In recent years, problems have continued to arise from these units, which appear to be related to the aging infrastructure, and the fact that many units may be nearing the end of their useful lives."

[31] According to EPA, Karst terraces are areas that are underlain by soluble bedrock, generally limestone or dolomite, and may contain extensive subterranean drainage systems and relatively large subsurface voids whose presence can lead to the rapid development of sinkholes. The Agency recognizes that rapid sinkhole formation that occurs in some karst terraces can pose a serious threat to human health and the environment by damaging the structural integrity of dams, liners, caps, run-on/run-off control systems, and other engineered structures. 75 Fed. Reg. 35,201.

[32] Illinois Environmental Protection Agency, Illinois EPA's Ash Impoundment Strategy Progress Report (October 2010), available at http://www.epa.state.il.us/water/ash-impoundment/documents/ash-impoundment-progress-102010.pdf.

[33] *Id.*

[34] US EPA, Coal Combustion Waste Damage Case Assessments (July 2007).

[35] *Supra* at note xxvi.

[36] US EPA, Database of Survey Responses, Information Requests from Electric Utilities, http://www.epa.gov/osw/nonhaz/industrial/special/fossil/surveys/survey5-16-11.pdf.

[37] *Id.*

[38] See Pines Ground Water Plume Site at http://www.epa.gov/region05/cleanup/pines/.

[39] See Thomas W. Easterly, Commissioner IDEM, State of Indiana Comments on Hazardous Waste Management System (Oct. 22, 2010), available at http://www.uswag.org/pdf/2010/CCR%20Comments/IDEM10222010.pdf.

[40] See US EPA, Toxic Release Industry dataset update for 2009 released in February 2010, available at http://www.epa.gov/triexplorer/.

[41] See Environmental Integrity Project and Earthjustice, *Out of Control: Mounting Damages from Coal Ash Waste Sites*, February 2010, available at http://earthjustice.org/sites/default/files/library/reports/ej-eipreportout-of-control-final.pdf and Environmental Integrity Project, Earthjustice and Sierra Club, In Harm's Way: Lack of Federal

Coal Ash Regulations Endangers Americans and Their Environment, August 2010, available at http://earthjustice.org/sites/default/files/files/report-in-harms-way.pdf.

[42] Ohio Admin. Code 3745:27-01(S)(23) (2010).

[43] *See* http://www.epa.gov/osw/nonhaz/industrial/special/fossil/surveys2/index.htm.

[44] National Academy of Sciences, National Research Council. Managing Coal Combustion Residuals in Mines, March 2006 at 78. Available at www.nap.edu.

[45] Environmental Integrity Project, Earthjustice and Sierra Club, In Harm's Way: Lack of Federal Coal Ash Regulations Endangers Americans and Their Environment, August 2010,, available at http://earthjustice.org/sites/default/files/files/report-in-harms-way.pdf.

[46] Stantec, Coal Combustion Facility Assessment Report (October 20, 2010), available at http://www.tva.gov/power/stantec2/Oct%202010%20presentation.pdf.

[47] Tenn. Comp. R & Regs. 1200-01-07-.01 et. seq.

[48] Tenn. Comp. R & Regs. 1200-01-07-.01(5). For further information see Southern Alliance for Clean Energy, "The State of Coal Ash Regulation In Tennessee", October 2010, available at http://www.cleanenergy.org/images/files/TN Regulatory and Damage Report1.pdf.

[49] US EPA, Coal Combustion Waste Damage Case Assessments, 20 (July 2007).

[50] 30 Tex. Admin. Code §§ 335.2(d): 335.1(138)(H)(2010).

[51] *Id.*

[52] *See* Clean Air Task Force, *Impacts on Water Quality from Placement of Coal Combustion Waste in Pennsylvania Coal Mines* (July 2006), available at www.catf.us.

[53] *Id.*

[54] Environmental Integrity Project, Earthjustice and Sierra Club, In Harm's Way: Lack of Federal Coal Ash Regulations Endangers Americans and Their Environment, August 2010, at pp. 243-247, available at http://earthjustice.org/sites/default/files/files/report-in-harms-way.pdf.

[55] U.S. Environmental Protection Agency, Office of Solid Waste. Coal Combustion Waste Damage Case Assessments. July 9,
2007. Downloaded from http://www.publicintegrity.org/assets/pdf/CoalAsh-Doc1.pdf.

[56] See Agency for Toxic Substances and Disease Registry, Health Consultation, Welsh Reservoir, Mount Pleasant, Titus County, TX, October 2009, available at http://www.atsdr.cdc.gov/hac/pha/pha.asp?docid=145&pg=1, and Health Consultation, Martin Creek Lake, Henderson, Rusk and Panola Counties, Texas, October 2009, available at http://www.atsdr.cdc.gov/HAC/pha/pha.asp?docid=117&pg=1.

[57] The three poor-rated impoundments are located at the Coleto Crek Power Station in Fannin, TX (two ponds) and the Lower Colorado River Authority in La Grange, TX (one pond). *See* U.S. Environmental Protection Agency, Coal Combustion Residuals Impoundment Assessment Reports available at http://www.epa.gov/osw/nonhaz/industrial/special/fossil/surveys2/index.htm#F.

[58] Battlefield Golf Club Site, Chesapeake, VA, http://www.epa.gov/reg3hwmd/CurrentIssues/finalr-battlefield_golf_club_site/index.html.

[59] The Chisman Creek Superfund Site contaminated residential wells with vanadium and selenium from coal ash generated by the Yorktown Power Station. *See* http://www.epa.gov/reg3hwmd/super/sites/VAD980712913/index.htm.

[60] Possum Point Power Station is listed as a "proven damage case" in EPA's 2007 *Coal Combustion Waste Damage Case Assessments* due to cadmium and nickel contamination of groundwater.

[61] Coal ash from the Clinch River Plant caused ecological damage to fish, snails, mussels, and aquatic macroinvertebrates in the Clinch River. In 1967 a dike from a coal ash pond at Clinch River Plant collapsed releasing a caustic ash slurry into the Clinch River. Some 217,000 fish were killed for up to 90 miles downriver and benthic macroinvertebrates, snails and mussels were also wiped out or very negatively affected. Forty years after the spill, aquatic ecosystems downstream remain degraded. High concentrations of copper and aluminum from power plant effluent also contribute to biotic impairment.

[62] http://www.epa.gov/osw/nonhaz/industrial/special/fossil/surveys2/dom-chesa-power-request.pdf.

[63] See US EPA, Toxic Release Industry dataset update for 2009 released in February 2010, available at http://www.epa.gov/triexplorer/.

Kentucky and Coal Ash Disposal in Ponds and Landfills [1]

Operator	Plant	Facility	County
Louisville Gas & Electric Co.	Cane Run Power Station	5 ponds/landfill*	Jefferson
Duke Energy Kentucky Inc	East Bend	3 ponds/landfill*	Boone
East Kentucky Power Coop Inc	HL Spurlock Power Station	1 pond/landfill*	Mason
East Kentucky Power Coop Inc	Cooper Power Station	landfill*	Pulaski
East Kentucky Power Coop Inc	Dale Power Station (EKPC)	2 ponds	Clark
Kentucky Utilities Co.	Ghent Power Station	5 ponds	Carroll
Kentucky Utilities Co.	Green River Power Station	5 ponds	Muhlenberg
Kentucky Power Co	Big Sandy Power Station (KPC)	2 ponds	Lawrence
Kentucky Utilities Co	EW Brown Power Station (KUC)	2 ponds/landfill*	Mercer
Kentucky Utilities Co	Tyrone Power Station	2 ponds	Woodford
Louisville Gas & Electric Co.	Trimble County (LGEC)	1 pond/landfill*	Trimble
Louisville Gas & Electric Co.	Mill Creek Power Station	5 ponds/landfill*	Jefferson
Owensboro City of	Elmer Smith (OMU)	landfill*	Daviess
Tennessee Valley Authority	Paradise Power Station	3 ponds	Muhlenberg
Pineville	Pineville Station	1 pond	
Tennessee Valley Authority	Shawnee Power Station	2 ponds/landfill*	McCracken
Western Kentucky Energy Corp.	DB Wilson (WKEC)	landfill*	Ohio
Western Kentucky Energy Corp	HMP&L Station Two Henderson (Henderson II	1 pond/landfill*	Henderson
Western Kentucky Energy Corp	Kenneth C. Coleman (WKEC)	3 ponds/landfill*	Hancock

* indicates one or more coal ash landfills.[2]

Amount of coal ash generated per year: Over 9 million tons. KY ranks 5th in the U.S for ash generation.[3]

According to a 2007 EPA risk assessment, 10 ponds and landfills in KY are unlined. Of these unlined sites, eight have no leachate collection systems and five have no groundwater monitoring systems.[4]

Number of Coal Ash Ponds: 43 ponds at 17 plants.[5] Kentucky has the third largest coal ash storage capacity (more than 64,000 acre-feet) in the nation.

Pond Ratings:. Eight ponds are rated "high hazard." Kentucky ties Ohio for the most high hazard dams (8) in the U.S. Six are rated "significant hazard."[6] Nineteen are not yet rated.[7] Many (20 0f 43) were not designed by a professional engineer, and most (27 of 43) were not constructed by one.

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[1] United States Environmental Protection Agency (U.S. EPA). Database of coal combustion waste surface impoundments (2009). Information collected by EPA from industry responses to Information Collection Request letters issued to the companies on March 9, 2009.

[2] U.S. Department of Energy's Energy Information Administration, Form EIA-767, Annual Steam-Electric Plant Operation and Design Data. 2005.

[3] U.S. EPA and United States Department of Energy (U.S. DOE). *Coal Combustion Waste Management at Landfills and Surface Impoundments, 1994-2004* (August 2006).

[4] RTI International. *Human and Ecological Risk Assessment of Coal Combustion Wastes, Draft* (August 6, 2007), prepared for the US Environmental Protection Agency.

[5] U.S. EPA. Database of coal combustion waste surface impoundments (2009).

***Age of Ponds*:** 33 ponds are over 30 years old, and 9 of those are over 40 years old.[8] The age of these ponds makes it unlikely that they have safeguards like liners and leachate collection systems. In fact, a 2007 EPA risk assessment mentions 10 unlined coal ash ponds in KY.[9] Others may exist.

***Capacity and releases**:* The EPA surface impoundment database contains storage capacity data for 19 of the 43 ponds in KY. These 19 ponds have a capacity of 88.5 million cubic yards. The 35 ponds for which size data are available cover an area of 1,857 acres. Five ponds at the Tyrone, Dale, E.W. Brown and Mill Creek power stations have had leaks or seepage, according to the EPA database. The pond at the Mill Creek Power Station has "major structural integrity issues." This pond is rated a "significant hazard" in case of structural failure.[10]

***Damage Cases**:* According to the U.S. EPA damage case assessment, potential damage cases in include[11]:

- Cinergy East Bend Scrubber Sludge Landfill: EPA cites allegations that an estimated 300 tons of sulfate per year was leaking into the Ohio River from the landfill. EPA found on-site exceedances for total dissolved solids, iron, and sulfate.

Earthjustice, Environmental Integrity Project and Sierra Club, documented three additional sites contaminated by coal ash:[12]

- Louisville Gas & Electric, Mill Creek Station: Groundwater monitoring found arsenic, sulfate and TDS exceeding federal standards in a contaminant plume one mile wide, potentially endangering off-site use of shallow drinking water wells.
- East Kentucky Power Cooperative, Spurlock Power Station: Coal ash landfill has contaminated groundwater since at least 2005 with arsenic, iron, sulfate and TDS. Arsenic has reached 16 times the drinking water standard in an off-site well. The disposal site discharges to three receiving streams that flow into the Ohio River.
- TVA Shawnee Fossil Plant: Onsite groundwater is contaminated with arsenic, boron, selenium, sulfate and TDS exceeding federal standards and health advisories.

Deficiencies of the Indiana Coal Ash Regulatory Program: State regulation of coal ash dams and landfills is minimal. There are no regular reporting requirements after dam construction, except for certificate renewal every five years. Operators are not given an inspection frequency and are not required to post a bond to ensure safe operation and maintenance or even completion of dam construction. Finally, Kentucky does not require emergency action planning or inundation mapping, which is astounding given the presence of eight high hazard dams that are likely to take human lives if they break and six significant hazard dams that would cause substantial economic and/or environmental damage in the event of failure. In addition, the state does not require composite liners at all ponds and landfills nor does the state prohibit dumping directly into the water table.

For more information, contact Lisa Evans, Earthjustice, 781-631-4119, levans@earthjustice.org.

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[6] *Id.*
[7] *Id.*
[8] *Id.*
[9] RTI International. *Human and Ecological Risk Assessment of Coal Combustion Wastes, Draft* (August 6, 2007), prepared for the US Environmental Protection Agency.
[10] U.S. EPA. Database of coal combustion waste surface impoundments (2009).
[11] U.S. EPA, Office of Solid Waste. *Coal Combustion Waste Damage Case Assessments* (July 9, 2007).
[12] Environmental Integrity Project, Earthjustice and the Sierra Club. In Harm's Way: Lack of Federal Coal Ash Regulations Endangers Americans and their Environment, August 26, 2010, http://earthjustice.org/sites/default/files/files/report-in-harms-way.pdf.

decreases at smaller scales. Models are becoming more comprehensive and sophisticated in representing observed climate and past climate changes; however, models continue to have significant limitations that lead to uncertainties in magnitude and timing, as well as regional details of predicting climate change (IPCC 2007). By taking the average of all models, known as the ensemble approach, a more accurate representation of the climate emerges (U.S. Climate Change Science Program 2008b). Global climate models are at this time imperfect and due to their uncertainties should not be used as a basis for public policy.

4.2.14.2 Cumulative Effects of Combustion of PRB Coal by Power Plants

Historically, the coal mined in the PRB has been used as one of the sources of fuel to generate electricity in power plants located throughout the U.S. Relatively little PRB coal, about 2 percent, is burned in Wyoming. Wyoming PRB coal is shipped primarily nationwide. In 2005, Wyoming coal went to 35 states besides Wyoming, although it can also be shipped overseas. The mines in the PRB have sold, and are expected to sell coal into the open coal market. Each mine's ability to sell coal in this market will determine annual production rates at that mine. Historically, the coal buyers have been domestic electric producers, although the coal could be used in other coal applications and it has been exported.

Coal sales are made on short term contracts, generally to individual power generators, or coal is sold on a spot market. This market is very dynamic and competitive. During the coal leasing EIS process, it is uncertain and speculative to predict who might purchase future PRB coal, how it would be used, and where the coal might be transported to. In the Northern American Electric Reliability Council (NERC) power regions where PRB coal is sold, coal use ranges from 74.2 percent in the upper Midwest, to 15.6 percent in the northeast U.S. (EPA 2007e).

Coal-burning power plants currently supply about 50 percent of the electric power generated in the U.S. The demand for power is increasing in the U.S. and throughout the world. According to a recent report by NERC, peak demand for electricity in the U.S. is expected to double in the next 22 years (Associated Press 2007). Many developing countries, including China and India, are also relying heavily on coal to meet their rapidly increasing power demands as coal is more economical and more available than other sources of electrical generation.

The regulatory mechanisms proposed under the Climate Security Act of 2008, as well as the past regulation of pollutants under the CAA, are imposed at the point when coal is burned and converted to electric energy. Over 95 percent of coal produced in the PRB is sold in an open market where coal is purchased on short term contracts or spot prices based on a coal feed stock that is suitable for each buyer's power generating facility. Coal production at any one mine is not tied in any predictable way over a period of time to any one power plant.

Power plant buyers attempt to buy coal from suppliers at the most economical prices that meet their needs. PRB coal has competed well in this market due to its low sulfur content, providing a way for electric generators to achieve acid rain reduction requirements. This makes it valuable in lowering sulfur dioxide (SO_2) pollution, as well as competitive mining costs when compared to delivered costs of coal from other coal producing areas.

Wyoming coal production has increased at a more rapid rate than other domestic coal. Coal coming out of the Wyoming PRB is mined using surface mining methods which are generally safer and less labor intensive than underground mining. Rural rangelands are the areas that are mainly mined; they are reclaimed according to WDEQ/LQD's standards (see Section 3.9.4). PRB coal reserves are in thick seams, resulting in more production from areas of similar land disturbance, and lower mining and reclamation costs.

Coal-fired power plants have been identified as principal sources of anthropogenic GHG emissions. Assuming that all coal produced from all coal mines in the Wyoming PRB would be burned to generate electricity; the amount of GHG emissions that could be attributed to that coal production can be estimated. This is done by relating the portion of coal mined in the PRB to the total emission of GHG from all coal mined in the U.S. It is assumed that all PRB coal is used for coal-fired electric generation as part of the total U.S. use of coal for electric generation. This gives an upper estimate of the GHG emissions resulting from the use of the total PRB coal production to produce electricity.

U.S. coal production increased from 1,029.1 million tons in 1990, when the Powder River Federal Coal Region was decertified, to 1,161.4 million tons in 2006, an increase of 12.9 percent (USDOE 2007a). Wyoming coal production increased from 184.0 million tons in 1990 to 444.9 million tons in 2006, an increase of 242 percent (Wyoming Department of Employment 1990 and 2006). The share of electric power generated by burning coal was consistently around 50 percent during that time frame. Also, the percentage of total U.S. CO_2 emissions related to coal consumption was consistently around 36 percent during that same time frame. The percentage of U.S. CO_2 emissions related to the coal electric power sector increased from about 30 percent in 1990 to about 33 percent in 2006 (USDOE 2009c).

In 2008, the Wyoming PRB coal mines produced approximately 451.7 million tons of coal. Using factors derived from laboratory analyses, it is estimated that approximately 749.6 million metric tons (tonnes) of CO_2 would be generated from the combustion of all of this coal (before CO_2 reduction technologies are applied). This number is based on an average Btu value of 8,600 per pound of Wyoming coal and using a CO_2 emission factor of 212.7 pounds of CO_2 per million Btu (USDOE 1994). The estimated 749.6 million tonnes of CO_2 represents approximately 35.3 percent of the estimated 2,125.2 million tonnes of U.S. CO_2 emission from coal combustion in 2008 (USDOE 2009c). In 2008, Wyoming PRB mines accounted for approximately 38.5 percent of the coal produced in the U.S. (USDOE 2009a).

According to the U.S. Department of Energy (USDOE), Energy Information Administration's (EIA's) 2008 Emissions of Greenhouse Gases in the U.S. report (USDOE 2009c) and EIA's 2008 U.S. Coal Report (USDOE 2009a):

- CO_2 emissions represent about 83 percent of the total U.S. greenhouse gas emissions.

- Estimated CO_2 emissions in the U.S. totaled 5,839.3 million tonnes in 2008, which was a 1.5 percent decrease from 2006 (which was 5,928.7 million tonnes).

- Estimated CO_2 emissions from the electric power sector in 2008 totaled 2,359.1 million tonnes, or about 40.6 percent of total U.S. energy-related CO_2 emissions in 2008 (which was 5,814.4 million tonnes).

- Estimated CO_2 emissions from coal electric power generation in 2008 totaled 1,945.9 million tonnes or about 33.5 percent of total energy-related CO_2 emissions and about 82.5 percent of CO_2 emissions from the U.S. electric power sector in 2008.

- Coal production from the Wyoming PRB represented approximately 43.4 percent of the coal used for power generation in 2008, which means that combustion of Wyoming PRB coal to produce electric power was responsible for about 12.8 percent of the estimated U.S. CO_2 emissions in 2008.

As discussed earlier in this chapter, Task 2 of the PRB Coal Review projects coal development in the PRB into the future for the years 2010, 2015, and 2020. Due to the variables associated with future coal production, two projected coal production scenarios (representing an upper and a lower production level) were developed to bracket the most likely foreseeable regional coal production level. In the low scenario, the percentage of coal use for electric generation would stay about the same, assuming that all forms of electric generation would grow at a proportional rate to meet forecast electric demand. In the high scenario, percentage of coal use would also remain about the same, but with PRB coal displacing coal from other domestic coal regions. Table 4-37 shows the estimated annual CO_2 emissions that would be produced from the combustion of all of this coal (before CO_2 reduction technologies are applied).

In the following analysis, the contribution of the pending LBAs (Table 1-2) to cumulative effects on the environment by historic and projected development activity is evaluated. To do this, it is assumed that coal mining will proceed in accordance with existing permit conditions. It is further assumed that this coal will be sold to coal users in response to forecasts of demand for this coal. Historically these users have been electric utilities in the U.S., although there is potential for sales outside the U.S. This coal market is open and competitive and users can buy from the most cost effective suppliers that meet their needs.

Table 4-37. Estimated Annual CO_2 Emissions from Projected PRB Coal Production Levels According to Task 2 or the PRB Coal Review[1].

Projected Coal Production Scenario	Year	Coal Production Rate (million tons per year)	CO_2 Emissions (million tonnes per year)
Lower	2010	411	682
	2015	467	775
	2020	495	821
Upper	2010	479	795
	2015	543	901
	2020	576	956

[1] BLM 2005a

The BLM does not determine the destination of this coal, and the use of the coal is determined by the coal consumer. The electric utilities where this coal has historically been used are throughout the U.S., and have a variety of coal combustion technologies and emission control, but all are licensed by the appropriate regulatory authorities in their locale, and operate under necessary permit requirements, and in compliance with regulation.

Table 4-38 shows the estimated cumulative annual CO_2e emissions produced by all mines in the PRB that currently have LBAs pending (listed in Table 1-2). The cumulative emissions calculated are those associated with the actual mining operations and not from the combustion of the coal produced and sold on the open coal market. The LBA tracts are addressed individually in the following EISs: the South Gillette Area Coal (SGAC) Lease Applications FEIS (BLM 2009g), the Wright Area Coal (WAC) Lease Applications EIS (this document), the West Antelope II Coal Lease Application FEIS (BLM 2008d), and the Hay Creek II Coal Lease Application DEIS (BLM 2010). Under the Proposed Actions and Alternatives 2 and 3, the three applicant mines (Black Thunder, Jacobs Ranch, and North Antelope Rochelle) anticipate producing coal included in the North Hilight Field, South Hilight Field, West Hilight Field, West Jacobs Ranch, North Porcupine, and South Porcupine LBA Tracts at or less than currently permitted levels using existing production and transportation facilities. Estimates of greenhouse gas emissions resulting from the specific mine operations at the Black Thunder, Jacobs Ranch, and North Antelope Rochelle mines from projected operations under the Proposed Actions and alternatives are also included in Section 3.18.2.

The CO_2 emissions related to burning coal that is produced from the three applicant mines to generate electricity would be extended as a result of leasing and mining the WAC LBA tracts. Table 4-39 shows the estimated annual coal production of each of the three applicant mines and the related annual CO_2 emissions that would be produced from the combustion of the coal produced from each of the six WAC LBA tracts as applied for and as reconfigured under Alternative 2 (BLM's preferred alternative), if this coal is burned to generate electric power. The total contribution of CO_2 emissions that would be produced

Table 4-38. Estimated Annual CO_2 Equivalent Emissions* from Coal Production at PRB Mines With Pending LBAs.

Source	2007	With LBA Tracts
Four SGAC Mines/Four LBA Tracts	0.716	1.182
Three WAC Mines/Six LBA Tracts	1.245	2.503
Antelope Mine/West Antelope II Tract	0.225	0.348
Buckskin Mine/Hay Creek II Tract	0.197	0.197
Total	**2.535**	**4.229**

* CO_2e in million metric tons (tonnes)
Source: BLM 2008g, J&S 2009, WWC 2009

from the combustion of all the coal produced from each tract, if this coal is burned to generate electricity, are shown in Table 4-39. A scenario resulting in the maximum possible annual CO_2 emissions from burning the coal produced from the WAC LBA tracts would occur assuming all six tracts were leased under Alternative 2, and that coal removal from all six tracts were to be sequenced to maintain each of the three applicant mines at full permitted production until the new reserves were fully depleted. Under this scenario, the Black Thunder Mine would be able to extend production for 14.2 years, the North Antelope Rochelle Mine for 11.4 years, and the Jacobs Ranch Mine for 22.8 years.

It is not possible to accurately project the level of CO_2 emissions that burning the coal from the six WAC LBA tracts would produce due to the uncertainties about what emission limits would be in place at that time or where and how the coal in these LBA tracts would be used if they are leased and the coal is mined. Furthermore, the rate of mining and the timing of when coal removal from the tracts would actually begin are only the applicant mines' best estimate. As shown in Tables 2-2 through 2-13, under the No Action alternatives the mines are projecting that after 2008 approximately 10 to 11 years of currently permitted mine life remains. Therefore, coal removal from these six proposed maintenance lease tracts would not begin until approximately 2018 or 2019. More rapid improvements in technologies that provide for less CO_2 emissions, new CO_2 mitigation requirements, or an increased rate of voluntary CO_2 emissions reduction programs could result in significantly lower CO_2 emissions levels than are projected here.

The three WAC applicant mines produced 228.3 million tons of coal in 2008, which represents about 50.5 percent of the coal produced in the Wyoming PRB in 2008. Combustion of those 228.3 million tons of coal to produce electricity produced approximately 378.7 million tonnes of CO_2 emissions, or about 5.4 percent of the total estimated anthropogenic CO_2 emissions produced in the U.S. in 2008, which was approximately 7,052.6 million tonnes (USDOE 2009c). Under the No Action Alternative, CO_2 emissions attributable to burning coal produced by the Black Thunder, Jacobs Ranch, and North Antelope Rochelle mines would be extended at about this level for up to approximately 10 years

Table 4-39. Estimated Annual CO_2 Emissions Produced from Combustion of Coal Produced from WAC LBA Tracts.

Applicant Mine/ LBA Tract	Anticipated Average Annual Coal Production by Applicant Mine[1] (mmtpy)	CO_2 Emissions Related to Annual Coal Production[2] (million tonnes)	Recoverable Coal Added Under Proposed Action[1] (mmt)	Mine Life Added Under Proposed Action[1] (years)	CO_2 Emissions Added by Proposed Action[2] (million tonnes)		Recoverable Coal Added Under Alternative 2[1] (mmt)	Mine Life Added Under Alternative 2[1] (years)	CO_2 Emissions Added by Alternative 2[2] (million tonnes)	
					Total per LBA Tract	Average per Year			Total per LBA Tract	Average per Year
Black Thunder/ North Hilight Field	135	224.0	263.4	2.0	437.1	218.5	652.8	4.8	1,083.0	225.6
Black Thunder/ South Hilight Field	135	224.0	213.6	1.6	354.4	221.5	304.3	2.3	504.8	219.5
Black Thunder/ West Hilight Field	135	224.0	377.9	2.8	626.9	223.9	965.2	7.1	1,601.3	225.5
Jacobs Ranch/ West Jacobs Ranch	40	66.4	669.6	16.7	1,110.9	66.5	912.6	22.8	1,514.0	66.4
North Antelope Rochelle/ North Porcupine	95	157.6	601.2	6.3	997.4	158.3	745.4	7.8	1,236.6	158.5
North Antelope Rochelle/ South Porcupine	95	157.6	309.7	3.3	513.8	155.7	339.3	3.6	562.9	156.4

1 Anticipated coal production rates at each applicant mine, coal tonnages within each LBA tract, and anticipated mine life added by each LBA tract are addressed in Chapter 2.
2 Determined using emission factor of 1.659 tonnes CO^2/ton of coal burned (USDOE 1994).

beyond 2008, while the mines recover their remaining estimated 2,483 million tons of currently leased coal reserves.

It is not likely that selection of the No Action alternatives would result in a decrease of U.S. CO_2 emissions attributable to coal mining and coal-burning power plants in the longer term, because there are multiple other sources of coal that, while not having the cost, environmental, or safety advantages, could supply the demand for coal beyond the time that the Black Thunder, Jacobs Ranch, and North Antelope Rochelle mines complete recovery of the coal in their existing leases.

In 2006, transportation sources accounted for approximately 29 percent of total U.S. GHG emissions (EPA 2008b). Transportation is the fastest growing source of U.S. GHGs, accounting for 47 percent of the net increase in total U.S. emissions since 1990. Transportation is also the largest end-use source of CO_2, which is the most prevalent GHG (EPA 2008b). Transportation is also the largest end-use source of CO_2, which is the most prevalent anthropogenic GHG (EPA 2008b, NOAA 2007).

Carbon dioxide is not the only GHG of concern. Another GHG, methane, in the form of coal bed natural gas (CBNG), is released into the atmosphere when coal is mined. The other major sources of U.S. methane emissions are from agriculture and waste management. According to the EIA (USDOE 2009a and 2009c):

- U.S. anthropogenic methane emissions totaled 722.7 million tonnes CO_2e in 2007 and 737.4 million tonnes CO_2e in 2008.

- U.S. 2008 methane emissions from coal mining were estimated at 82.0 million tonnes CO_2e, which represents approximately 11.1 percent of the U.S. total anthropogenic methane emissions in 2008.

- Surface coal mining operations in the U.S. were estimated to be responsible for methane emissions of about 15.7 million tonnes of CO_2e in 2008, which represents about 2.1 percent of the estimated U.S. anthropogenic methane emissions in 2008, and about 19.1 percent of the estimated methane emissions attributed to coal mining of all types.

- The Wyoming PRB produced approximately 55.5 percent of the coal mined in the U.S. in 2008 using surface mining techniques, which means that Wyoming PRB surface coal mines were responsible for approximately 1.17 percent of the estimated U.S. anthropomorphic methane emissions in 2008. The three applicant mines (Black Thunder, Jacobs Ranch, and North Antelope Rochelle) contributed about 50.5 percent of the Wyoming PRB production in 2008, which is the equivalent of about 4.4 million tonnes CO_2e vented methane emissions. It should be noted that the estimated amount of annual methane emissions vented from the applicant mines based on the gas content analyses of local coal

cores (Section 3.18.2) is more than 20 times less than this estimate that is based on EIA's 2009 report (USDOE 2009c).

Since 1990, when BLM began leasing using the lease by application (LBA) process, total U.S. anthropogenic methane emissions declined from 783.5 million tonnes CO_2e to 737.4 million tonnes CO_2e in 2008. Total coal mining related emissions declined from 106.4 million tonnes CO_2e to 82.0 million tonnes CO_2e during the same time period. The EIA attributes the overall decrease in coal mine emissions of methane since 1990 to the fact that the coal production increases during that time had been largely from surface coal mines that produce relatively little methane (USDOE 2009c).

CBNG is currently being commercially produced on a large scale by oil and gas operators from wells located within and near the WAC LBA tracts. CBNG that is not recovered prior to mining would be vented to the atmosphere during the mining process. Selection of the No Action alternatives would potentially allow more complete recovery of the CBNG from the six WAC LBA tracts in the short term (roughly 10 years), during the time that the three applicant mines' currently leased coal is being recovered. However, BLM's analysis suggests that a large portion of the CBNG resources that are currently present on the tract would be recovered prior to mining under the Proposed Action or Alternatives 2 or 3 (a complete discussion is included in Section 3.3.2.1.2.1). Selection of the No Action alternatives would not be likely to directly decrease U.S. methane emissions attributable to coal mining in the long term because there are multiple other sources of coal that could supply the coal demand beyond the time that the Black Thunder, Jacobs Ranch, and North Antelope Rochelle mines recover the coal in their existing leases.

Nitrous oxide (N_2O) is the one other GHG of concern that is associated with coal mining; however, the largest source in the U.S. is agricultural (about 76 percent comes from fertilization of soils and about 24 percent from management of animal waste) (USDOE 2009c).

Specific levels of significance have not yet been established for GHG emissions, and given the current state of science, it is not yet possible to associate specific actions with the specific climate impacts. As a consequence, impact assessments of effects of specific anthropogenic activities cannot be performed. Tools necessary to quantify incremental climatic changes associated with these GHG emission estimates for the projected coal mine development activities in the PRB are presently unavailable. Technology to conduct such an analysis at this spatial and temporal scale simply does not exist; therefore, conclusions as to the magnitude or significance of the emissions on climate change cannot be reached. The impacts of climate change represent the cumulative aggregation of all worldwide GHG emissions, land use management practices, and the albedo effect. The analysis does provide a meaningful context and measure of the relative significance of coal use from the overall projected PRB coal production on total GHG emissions. Therefore, climate change analysis in this EIS is limited to accounting for and disclosing of factors that contribute to

climate change. To the extent that emission data were available or could be inferred from representative type data, potential GHG emissions that could result from development of the pending LBA tracts in the PRB (Table 1-2) have been identified, as well as emissions that would result from selection of the No Action alternatives.

Although the effects of GHG emissions and other contributions to climate change in the global aggregate are estimable, given the current state of science it is impossible to determine what effect any given amount of GHG emissions resulting from an activity might have on the phenomena of global warming, climate change, or the environmental effects stemming from it. It is therefore not currently possible to associate any particular action and its specific project-related emissions with the creation or mitigation of any specific climate-related effects at any given time or place. However, it is known that certain actions may contribute in some way to the phenomenon (and therefore the effects of) climate change, even though specific climate-related environmental effects cannot be directly attributed to them.

4.2.14.3 U.S. Actions and Strategies to Address Greenhouse Gas Emissions

Potential regulatory policies to address climate change are in various stages of development at the federal, state, and regional levels (USDOE 2009b). A number of bills have been introduced in the U.S. Congress related to global climate change. At this time, there is no national policy or law in place that regulates GHG emissions.

The Lieberman-Warner Climate Security Act, which was introduced in October 2007 by Senators Joseph I. Lieberman (ID-CT) and John W. Warner (R-VA), would establish a cap-and-trade within the United States. In short, the "cap" would set a legal limit on the quantity of greenhouse gases that a region can emit each year and "trade" would allow companies to exchange the permission – or permits – to emit greenhouse gases. The cap would get tighter over time, until by 2050, emissions would be reduced by 63 percent below 2005 levels. The bill was approved by the Senate Environment and Public Works Committee in December, 2007 (http://www.pewclimate.org, accessed 12/21/2007). The bill was introduced in the Senate and read the first time on May 20, 2008. The Boxer-Lieberman-Warner substitute amendment to the Climate Security Act of 2008 was subsequently released by the Senate Environment and Public Works Committee on May 21, 2008. The bill was then read a second time and placed on the Senate Legislative Calendar under General Orders, Calendar No. 742. In June 2008 the U.S. Senate voted to invoke cloture on the Boxer amendment but did not pass the cap-and-trade legislation.

On June 26, 2009, the U.S. House of Representatives passed The American Clean Energy and Security Act of 2009. The legislation includes a federal GHG emissions cap-and-trade program that would take effect in 2012. The declining emissions cap requires that total GHG emissions be 17 percent below 2005 levels by 2020 and 83 percent below 2005 levels by 2050. In November 2009,

U.S. Department of the Interior
Bureau of Land Management
Uncompahgre Field Office
2465 South Townsend Avenue
Montrose, CO 81401

ENVIRONMENTAL ASSESSMENT

NUMBER: DOI-BLM-CO-150-2008-53 EA

CASEFILE/PROJECT NUMBER: COC70615

PROJECT NAME: Elk Creek East Tract Coal Lease

LEGAL DESCRIPTION:

T.13S., R.90W., 6th PM,
Sec. 3: Portion of W½;
Sec. 4: N½ and Portion of N½S½;
Sec. 5: Portion of E½.

APPLICANT: Oxbow Mining, LLC

PURPOSE AND NEED FOR THE PROPOSED ACTION

Oxbow Mining, LLC (OMLLC) has submitted a Lease-by-Application (LBA) to the Bureau of Land Management (BLM) seeking to lease BLM mineral estate under public lands located adjacent to their currently operating coal mine (the Elk Creek Mine). The BLM action is to decide whether or not to lease the coal in response to the LBA. The purpose of this action is to evaluate the expanded development and mine operations of the Elk Creek East Tract (ECET), to continue producing coal at, or near, current levels for approximately 1 additional year. The need to prepare an environmental assessment in accordance with the National Environmental Policy Act (NEPA) was triggered when OMLLC submitted a Land Use LBA. The BLM is responding to an application to lease coal resources and is preparing an EA. The EA will analyze the action to provide access to Federal lands for the extraction of the coal resources, as established by the Mineral Leasing Act (MLA) of 1920, as amended by the Federal Coal Leasing Amendments Act (FCLAA) of 1976, and the Federal Land Policy and Management Act (FLPMA) of 1976.

BACKGROUND/INTRODUCTION

Currently, OMLLC operates the Elk Creek Mine, which is an underground longwall coal mine just north of the town of Somerset, Colorado (**Figure 1**). Coal mining has been conducted in the North Fork Valley for over 100 years. The Elk Creek Mine has been in operation since 2002, and produces approximately 5,000,000 tons of coal annually. The ECET would provide a logical extension of OMLLC's D-Seam workings within the current Elk Creek Mine. It would also allow the mine to continue producing coal at the current rate, instead of ceasing production as recoverable leased coal reserves are exhausted. The decision to lease these lands is a necessary requisite for mining, but is not in itself the enabling action that will allow mining. The most

Proposed Action is to continue mining operations into an additional area. That is, the action would not constitute adding 3.96 million tons of coal to the existing 4.8 million tons; mining the 3.96 million tons would be in place of the prior 4.8 million tons.

The air quality analysis conducted for the original mine included an emissions inventory and modeling analysis. That emissions inventory quantifies PM_{10}, NOx, and SO_2 emissions. The modeling analysis also includes a visibility impacts assessment in the West Elk Wilderness Area as well as an atmospheric deposition impacts assessment. Emissions that were calculated and modeled included tailpipe emissions from mining equipment, haul trucks, and locomotives (railway emissions). The results of that detailed impact assessment predicted no significant impacts to air quality as a result of authorizing the Oxbow mine.

The proposed expansion of the mine is for 3.96 million tons of coal annually, and the emissions-generating equipment used will be less than levels analyzed for the Elk Creek Coal Lease Tract in 2000. That is, the equipment used for the mine expansion will be the same equipment that is being used in the current mining operations. Therefore, the air quality impacts associated with the proposed mine expansion can be presumed to be equal to, or less than, impacts predicted in the original air quality impact assessment. The air quality assessment for this EA tiers to that original assessment.

Since the FEIS for Elk Creek Coal Lease Tract was a combined analysis for three lease tracts, the specific quantities of emissions and air quality impacts associated with the Elk Creek Coal Lease Tract were not brought forward in this EA; rather those emissions quantities and associated impacts are tiered to in this EA. To view the quantified emissions inventory and air quality impacts assessment, see Final Environmental Impact Statement Iron Point Exploration License; Iron Point Coal Lease Tract; Elk Creek Coal Lease Tract Delta and Gunnison Counties, Colorado, USFS and BLM 2000. Appendix M, *Air Quality Impacts Assessment,* contains the detailed air quality impact assessment.

Moreover, in relation to railway emissions, due to more stringent regulations since the FEIS was written, the EPA predicted that, on a nationwide average, NOx emissions from locomotives in the year 2010 would be about 40 percent less than emissions compared to 1999 levels (FEIS, page 3-7). The FEIS air quality impact analysis, which relied on emissions factors for 1999, determined NOx emissions to be insignificant; therefore, it can be presumed that NOx emissions associated with locomotives from the proposed mine expansion would decrease when compared to previous levels.

The Proposed Action Alternative would provide a logical extension to the mine's current D-Seam workings at a lower production rate of 3.96 million tons of coal annually, as compared to its current production levels. The total generation of air pollutants (including carbon monoxide, particulate matter, including PM2.5 and PM10, oxides of nitrogen, and VOCs) would be less than (or, on a short-term basis, equivalent to) current emissions. Therefore, activities under the Proposed Action Alternative are not anticipated to require a modification of the existing construction permit, and are not expected to exceed the NAAQS.

Combustion

Historically, the coal mined in Colorado has been used as one of the sources of fuel to generate electricity in power plants located throughout the U.S., and shipped overseas. The mines in Colorado have sold, and are expected to sell, coal into the open coal market. The mine's ability

to sell coal in this market is determined by the annual production rates at that mine. Coal sales are made on short term contracts or sold on a spot market. This market is very dynamic and competitive. During the coal lease application process, it is uncertain and speculative to predict who might purchase future Colorado coal, how it would be used, and where the coal might be transported to. Moreover, the restrictions and control measures vary by the location in which the coal is burned.

Coal-burning power plants currently supply about 50 percent of the electric power generated in the U.S. The demand for power is increasing in the U.S. and throughout the world. According to a recent report by the North American Electric Reliability Corporation, peak demand for electricity in the U.S. is expected to double in the next 22 years (Associated Press 2007). Many developing countries, including China and India, are also relying heavily on coal to meet their rapidly increasing power demands as coal is more economical and more available than other sources of electrical generation. The regulatory mechanisms proposed under the Climate Security Act of 2008, as well as the past regulation of pollutants under the CAA, are imposed at the point when coal is burned and converted to electric energy. A percentage of coal produced in Colorado is sold in an open market where coal is purchased on short term contracts or spot prices based on a coal feed stock that is suitable for each buyer's power generating facility. Coal production at any one mine is not tied in any predictable way over a period of time to any one power plant.

According to the U.S. Energy Information Administration (2009), nearly 94 percent of all coal consumed in the U.S. during 2009 was used in the generation of electric power. Because of this, it can reasonably be assumed that the coal will be shipped to a coal-fired power plant. It would be possible to provide a quantification of GHG emissions associated with the burning of the mined coal at a specific facility; however, the types and location of the facilities the coal might be processed in is speculative and not foreseeable. The terms of the agreements between the coal combustion facilities and the coal company are not within the regulatory authority of the BLM. The contractual agreements between the coal plant and the coal company are outside the scope of this analysis, and the BLM does not determine at which facilities the coal is used. The EPA and state governments where the coal is burned provide the regulatory emissions standards for the combustion of the coal. Different emissions control devices on a power plant could greatly affect the amount of carbon dioxide that is released into the atmosphere. (For example, a power plant that practices CO_2 capture would ultimately release a much smaller quantity of CO_2 than a traditional power plant that is 50 years old.)

In order to calculate the CO_2 equivalent emissions from coal, the following information would be needed:

- the number of tons of coal produced per year from a mine;
- the heat content of that coal in BTUs per ton; and
- the facility in which the coal is slated to be burned.

Even though the BLM cannot reasonably predict the destination of where the coal will be burned, it is still possible to do emissions calculation if the number of tons of coal produced per

year from a mine, and the heat content of that coal in BTUs per ton, is known. This information is known for the proposed lease tract. However since the type of facility the coal might be processed in (i.e., the control efficiency of the facility) is speculative; calculations were made using average numbers in U.S. facilities. Therefore the emissions calculation does not represent an accurate estimate of potential GHG emissions from this specific project. That said, assuming the Proposed Action Alternative would generate 3.96 million tons of high-quality low-sulfur super-compliant bituminous coal per year, with an average heat content of 24.2 million British thermal units (BTUs) per ton, nearly 9.6 million metric tons of carbon dioxide equivalent (CO_2e) would be emitted. This amount represents nearly 8 percent of all CO_2e emissions in Colorado during 2007, nearly 0.14 percent of all CO_2e emissions in the U.S. during 2007, and nearly 0.04 percent of global CO_2 emissions during 2007 (CAIT-US 2011). These calculations are based upon default emission factors for stationary combustion in the Energy Industries (IPCC 2006), assuming no other use of the coal and complete total combustion, and therefore represent a conservative overestimate of potential GHG emissions.

EPA Regulations

In its *Endangerment and Cause or Contribute Findings for Greenhouse Gases under Section 202(a) of the Clean Air Act*, the EPA determined that GHGs are air pollutants subject to regulation under the CAA. The EPA is in the early stages of determining how to regulate carbon dioxide, methane, nitrous oxide, sulfur hexafluoride, hydrofluorocarbons, and perfluorocarbons. As of March 2011, the EPA has not set GHG emission limits for stationary sources. However, the EPA is gathering detailed GHG emission data from thousands of facilities throughout the U.S., and will use the data in order to develop an improved national GHG inventory, as well as to establish future GHG emission control regulations. Beginning in 2010, many facilities across the US, including coal fired power plants, estimated GHG emissions in accordance with the EPA's "Greenhouse Gas Mandatory Reporting Rule" and will report annual GHG emissions beginning on March 31, 2011.

Beginning in 2011, GHG emissions from some facilities will become subject to Federal air quality permitting programs, such as the Title V Operating Permit Program and the Prevention of Significant Deterioration (PSD) Program. Historically, GHG emissions were not measured by facilities under these programs, and air quality permits did not address greenhouse gases. However, the EPA, as well as State and local air quality permitting agencies, will begin reviewing GHG emissions under these programs in accordance with the EPA's "Prevention of Significant Deterioration and Title V Greenhouse Gas Tailoring Rule." This review may lead to more accurate estimates of GHG emissions from these facilities, and may prompt GHG emission monitoring in some cases.

Based largely upon GHG emission data submitted under the Mandatory Reporting Rule, the EPA plans to develop stationary source GHG emissions reduction rules that could mandate substantial reductions in U.S. greenhouse gas emissions. Alternatively, Congress may develop cap-and-trade legislation as another means to reduce GHG emissions. Consequently, a GHG emissions calculation for coal burned at a power plant is likely to be increasingly regulated in the near future. The first EPA regulation to limit emissions of GHGs imposed carbon dioxide emission standards on light-duty vehicles, including passenger cars and light trucks (GPO 2010e). As of February 2011, the EPA had not set GHG emission limits for stationary sources (such as compressor stations); however, the EPA is gathering detailed GHG emission data from thousands of facilities throughout the U.S., and will use the data in order to develop an improved national GHG inventory, as well as to establish future GHG emission control regulations.

Human and Ecological Risk Assessment of Coal Combustion Wastes

April 2010

DRAFT

U.S. Environmental Protection Agency
Office of Solid Waste and Emergency Response
Office of Resource Conservation and Recovery

Regulation Identifier Number (RIN) 2050-AE81

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Human and Ecological Risk Assessment of Coal Combustion Wastes

DRAFT

U.S. Environmental Protection Agency
Office of Solid Waste and Emergency Response
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List of Acronyms

Acronym	Definition
3MRA	multimedia, multiple exposure pathway, multiple receptor risk assessment
ADD	average daily dose
Ag	silver
Al	aluminum
As	arsenic
ATSDR	Agency for Toxic Substances and Disease Registry
B	boron
Ba	barium
BCF	bioconcentration factors
Be	beryllium
CAIR	Clean Air Interstate Rule
CalEPA	California EPA
CAMR	Clean Air Mercury Rule
CCW	coal combustion waste
Cd	cadmium
Co	cobalt
Cr	chromium
CSCL	chemical stressor concentration limit
CSF	cancer slope factor
Cu	copper
DAF	dilution attenuation factor
DBGS	depth below ground surface
DOE	U.S. Department of Energy
DWAK	Drinking Water Action Level
EFH	Exposure Factors Handbook
EIA	Energy Information Agency
EPA	U.S. Environmental Protection Agency
EPACMTP	EPA's Composite Model for Leachate Migration with Transformation Products
EPRI	Electric Power Research Institute
F	fluoride
FBC	fluidized-bed combustion
Fe	iron
FGD	flue gas desulfurization
GIS	geographic information system
HBN	health-based number
HDPE	high-density polyethylene
HEAST	Health Effects Assessment Summary Tables
HELP	Hydrologic Evaluation of Landfill Performance
Hg	mercury
HGDB	Hydrogeologic Database
HHRAP	Human Health Risk Assessment Protocol
HQ	hazard quotient

Acronym	Definition
ID	identification
IEM	Indirect Exposure Methodology
IRIS	Integrated Risk Information System
IWEM	Industrial Waste Evaluation Model
LADD	lifetime average daily dose
LDS	leak detection system
LF	landfill
LOAEL	lowest observed adverse exposure level
MCL	maximum concentration limit
Mn	manganese
MINTEQA2	a geochemical assessment model for environmental systems
Mo	molybdenum
MRL	minimal risk level
MSW	municipal solid waste
Ni	nickel
NOAEL	no observed adverse exposure level
NPDES	National Pollutant Discharge Elimination System
ORD	Office of Research and Development (EPA)
Pb	lead
PCS	Permit Compliance System
pH	a measure of hydrogen ion activity
RCRA	Resource Conservation and Recovery Act
RCRA	Resource Conservation and Recovery Act
RfD	reference dose
RME	reasonable maximum exposure
SAB	Science Advisory Board (EPA)
Sb	antimony
SD	standard deviation
Se	selenium
SI	surface impoundment
Sr	strontium
SW	solid waste
SWTSS	surface water total suspended solids
TCLP	toxicity characteristic leaching procedure
Tl	thallium
TL3	trophic level 3
TL4	trophic level 4
TSS	total suspended solids
UF	uncertainty factor
USGS	U.S. Geological Survey
V	vanadium
WMU	waste management unit
Zn	zinc

Human and Ecological Risk Assessment of Coal Combustion Wastes – Executive Summary

The Executive Summary of EPA's *Human and Ecological Risk Assessment of Coal Combustion Wastes* is organized into four parts. First, it presents **Background** for the regulation and study of coal combustion wastes. Next, it discusses the **Risk Assessment Methodology** used to evaluate these wastes' potential impact on human health and the environment. The Executive Summary continues with the presentation of the report's **Results and Characterization**. Finally, it discusses the overall **Conclusions** of the report.

Background

The U.S. Environmental Protection Agency (EPA) is evaluating management options for solid wastes from coal combustion: fly ash, bottom ash, boiler slag, flue gas desulphurization (FGD) residues, and fluidized bed combustion (FBC) wastes. In this report, these five types of coal combustion wastes are referred to as coal combustion waste (CCW). All coal-fired electric utility plants in the United States generate at least one of these wastes, and most generate more than one. For example, most electric utility plants generate fly ash and either bottom ash or boiler slag.[1] Some plants also generate FGD residues.[2] Coal-fired electric utility plants that use FBC technology generate both bottom ash (bed ash) and fly ash.

Depending on the coal-fired power plant boiler and air pollution control technologies employed at the power plants, these five types of CCW might be initially generated either as primarily dry or primarily wet material. Typically, the dry materials are disposed of in landfills, while the wet materials are disposed of, at least initially, in surface impoundments (the settled solids can be removed periodically and disposed of in landfills). Landfills and surface impoundments are referred to as waste management units (WMUs).

Coal-fired power plants typically conduct coal preparation activities before burning the coal in their boilers. Wastes from these coal preparation activities (such as coal handling by conveyor systems, coal washing for removing mineral matter, and coal "sizing"—for example, reducing particle sizes of coal for firing in a pulverized coal boiler) are not part of the Bevill exclusion under the federal Resource Conservation and Recovery Act. However, in the past, some U.S. coal-fired power plants have managed CCW together with these coal preparation wastes, or "coal refuse," in the same landfills and surface impoundments. Because the chemical characteristics of the coal refuse can affect the amount and behavior of chemical constituents in the CCW,[3] EPA designed this analysis specifically to estimate risks from CCW management that is conducted separately from coal refuse management, as well as to estimate risks from CCW that is comanaged with coal refuse.

This report describes the results of a national-scale analysis of groundwater impacts of managing CCW in five separate scenarios:

- CCW managed alone in landfills
- CCW managed alone in surface impoundments
- CCW comanaged with coal refuse in landfills

[1] U.S. EPA (1999a), Figure 3-2.
[2] U.S. EPA (1999a), Figure 3-3.
[3] U.S. EPA (1999a), page 3-18.

- CCW comanaged with coal refuse in surface impoundments
- FBC waste managed in landfills.

This risk assessment was designed and implemented to identify and quantify human health and ecological risks that may result from groundwater contamination from current management practices for high-volume CCWs. The risk assessment uses mathematical models to represent either a landfill or a surface impoundment, and to represent the movement of chemical constituents from the CCW placed into a landfill or surface impoundment through the environment, up to an exposure point where the chemical constituent comes into contact with a person (such as in a glass of drinking water from a well) or an aquatic organism (such as a fish swimming in surface water that has become contaminated by groundwater that discharges into the stream near a CCW landfill). In this analysis, EPA evaluated human health exposures that occur by the groundwater-to-drinking-water pathway, human health exposures that occur by fish consumption, ecological exposures of aquatic organisms in direct contact with contaminated surface water or sediment, and ecological exposures of organisms that eat contaminated food items from those contaminated nearby surface water bodies.

Because the infiltration from a landfill or surface impoundment can significantly influence how much, and how quickly, leachate flows out of a waste management unit, the models also account for three types of liner scenarios: unlined, clay-lined, and composite-lined. An unlined waste management unit has native soils as the bottom and sides; a clay-lined unit has a certain amount of clay present to slow the flow of leachate; and a composite-lined unit is constructed from various layers, including human-made materials, which are assumed to retard the leachate flow to a significantly greater extent than a clay liner.

The risk assessment provides a distribution of estimated risks for each of the five scenarios and three liner types. EPA modeled CCW waste management units that were located across the United States, in locations that represent a subset of the coal-fired power plants that were in use in the mid-1990s. The models used to represent the movement of chemical constituents from a landfill or surface impoundment through the environment rely on data such as weather patterns, soil types, and subsurface geology, which influence the speed and direction in which the chemical constituents move. Thus, the environmental setting, or geographic location, of a landfill or surface impoundment can influence the resulting estimated risk. By conducting the analysis at a national scale, EPA estimated risks at locations across the United States.

Risk Assessment Methodology

To estimate the risks posed by the onsite management of CCW, the risk assessment determined the release of CCW constituents from landfills and surface impoundments, estimated the concentrations of these constituents in environmental media, and estimated the risks that these concentrations pose to human and ecological receptors. To evaluate the significance of these risks, they were compared with a risk range or single criterion as follows:

- For constituents that cause cancer (carcinogens), the typical cancer risk evaluated was a range from 1 excess lifetime cancer case per 1,000,000 exposed individuals (i.e., 10^{-6} excess cancer risk) to 1 case per 10,000 exposed individuals (i.e., 10^{-4} excess lifetime cancer risk).[4]

[4] This is the typical cancer risk range used by the Office of Solid Waste and Emergency Response - (10^{-6} to 10^{-4}).

- For constituents that cause adverse, noncancer health effects (noncarcinogens), the criterion is a hazard quotient (HQ)[5] of greater than 1
- For constituents that cause adverse ecological effects, the criterion is an HQ of greater than 1.

In support of this risk assessment, EPA assembled a constituent database that includes leachate and porewater waste concentrations for 41 CCW constituents taken from more than 140 CCW disposal sites around the country. The CCW risk assessment subjected these waste and leachate constituent concentrations to a risk assessment methodology that implemented the following steps to assess the human and ecological risks posed by CCW:

- **Hazard Identification,** which collected existing human health and ecological benchmarks for the 41 CCW constituents to identify the 25 chemicals with benchmarks for constituent screening
- **Constituent Screening,** which compared very conservative estimates of exposure concentrations (e.g., whole waste concentrations, leachate concentrations) to health-based concentration benchmarks to quickly and simply eliminate constituents and exposure pathways that did not require further analysis
- **Full-Scale Analysis,** which used a Monte Carlo probabilistic analysis to characterize the risks to human health and ecological receptors from onsite disposal of CCW constituents that posed the greatest potential risks in the screening analysis.

To select the constituents for full-scale modeling, the screening analysis compared very conservative estimates of exposure concentrations (e.g., leachate concentrations) to health-based concentration benchmarks to quickly and simply identify constituents that do not appear to pose human or ecological health concerns, so that these constituents could be eliminated from further analysis. For example, leachate concentrations were compared directly to drinking water standards, which is equivalent to assuming that human receptors are drinking leachate.

During both the screening and probabilistic modeling stages, two exposure scenarios were evaluated for humans:

- Contaminated groundwater being transported to drinking water wells from a CCW landfill or surface impoundment
- Contaminated groundwater discharging into a surface waterbody where people catch and eat fish.

Constituents addressed in the full-scale analysis were those that posed the greatest potential risks to human or ecological health. The full-scale analysis was designed to characterize waste management scenarios based on two WMUs (landfills and surface impoundments), three waste types (CCW, CCW codisposed with coal refuse, and FBC waste), and three liner types (unlined, clay-lined, and composite-lined). Because FBC waste is not known to be disposed of in surface impoundments, this left 15 possible disposal options to model. These options provide a good representation of CCW disposal practices and waste chemistry conditions that affect the release of CCW constituents from WMUs.

The full-scale analysis was implemented using a probabilistic approach that produces a distribution of risks or hazards for each receptor by allowing the values of some of the parameters in the analysis to vary. This approach is ideal for this risk assessment because there are so many CCW facilities across the United States, and the approach

[5] The HQ is the ratio of the average daily exposure level to a protective exposure level corresponding to the maximum level at which no appreciable effects are likely to occur.

captures the variability in both waste management practices and environmental settings (e.g., hydrogeology, climate, hydrology). This probabilistic approach was implemented through the following steps:

1. Characterize the CCW constituents and waste chemistry, along with the WMUs in which each waste stream may be managed (i.e., the size and linear status of CCW landfills and surface impoundments).
2. Characterize the environmental settings for the sites where CCW landfills and surface impoundments are located (i.e., locations of coal-fired power plants).
3. Identify how contaminants are released from a WMU through leaching and transported to human and ecological receptors by groundwater and surface water.
4. Predict the fate, transport, and concentration of constituents in groundwater and surface water once they are released to groundwater from the WMUs and travel to receptors at each site.
5. Quantify the potential exposure of human and ecological receptors to the contaminant in the environment.
6. Estimate the potential risk to each receptor from the exposure and characterize this risk in terms of exposure pathways and health effects.

Based on this approach, EPA characterized the potential risks associated with the waste disposal scenarios and exposure pathways, including the uncertainties associated with the results.

Results and Characterization

The CCW risk assessment presented results at a typical exposure (50th percentile) as well as a high-end exposure (90th percentile). CCW risk assessment results at the 90th percentile suggest that managing CCW in unlined or clay-lined WMUs result in risks greater than the risk criteria of an HQ greater than 1 for noncancer effects to both human and ecological receptors (for humans drinking groundwater, 90th percentile HQs up to 3 for antimony, 7 for boron, 9 for lead, 8 for molybdenum, 20 for nitrate, and 4 for thallium; for ecological receptors, 90th percentile HQs up to 2,000 for boron, 300 for lead, 100 for arsenic, 30 for cadmium, and 12 for selenium). With respect to arsenic in CCW, the 90th percentile results suggest that managing CCW in unlined or clay-lined WMUs results in human excess cancer risks within or above a range of 1 in 1 million to 1 in 10,000 (i.e., ranging from 6 in 100,000 to 1 in 50 excess cancer risk). Clay-lined units tended to have lower risks than unlined units, but still had 90th percentile arsenic III excess cancer risks ranging from 6 in 100,000 to 7 in 1,000.However, it was the composite-lined units that effectively reduced risks from all pathways and constituents, below1 in 100,000 excess cancer risk or an HQ of one.

The tables that follow present selected risk results only for chemicals that exceed an excess cancer risk of 1 in 100,000 (arsenic only) or an HQ of 1.

As shown in **Table ES-1**, arsenic was the constituent with the highest risk for landfills. Clay-lined landfills presented 90th percentile arsenic III cancer risks as high as 1 in 5,000 and thallium HQs as high as 2. When landfills were unlined, they additionally presented arsenic III cancer risks as high as 1 in 2,000 and a maximum thallium HQ of 3. In addition to arsenic and thallium, clay-lined FBC landfills also presented 90th percentile risks above an HQ of 1 for antimony. However, unlined FBC landfills differed in that they only exceeded a 1 in 100,000 excess cancer risk for arsenic and did not exceed an HQ of 1 for any of the noncarcinogens modeled.[6] At the 50th percentile (see **Table ES-2**) arsenic

[6] Unlined FBC units showed less risk as modeled.

III from CCW codisposed with coal refuse exceeded an excess cancer risk of 10^{-5}, with cancer risks of 1 in 50,000.

As shown in **Table ES-3**, arsenic and cobalt were the constituents with the highest risks for surface impoundments. Clay-lined surface impoundments presented 90th percentile excess cancer risks above 1 in 10,000 for arsenic and exceed the HQ criterion of 1 for boron, cadmium, cobalt, molybdenum, and nitrate. Here, arsenic excess cancer risks were as high as 1 in 500, and cobalt had HQs as high as 200. When surface impoundments were unlined, they also showed risk above the HQ criterion for lead and selenium. Here, arsenic excess cancer risks were as high as 1 in 50, and cobalt had HQs as high as 500. As seen in **Table ES-4**, the 50th percentile surface impoundment results exceeded a 1 in 100,000 cancer risk for arsenic and only cobalt exceeded an HQ of 1. Here, unlined units had arsenic excess cancer risks as high as 6 in 10,000 while clay-lined units had arsenic excess cancer risks as high as 1 in 5,000. Cobalt HQs were as high as 20 and 6 for unlined and clay-lined surface impoundments, respectively.

For the groundwater-to-drinking-water pathway, composite liners, as modeled in this assessment, effectively reduced risks from all constituents to below a 10^{-5} cancer risk or HQ of 1 for both landfills and surface impoundments at the 90th and 50th percentiles.

For the groundwater-to-drinking-water pathway, arrival times of the peak concentrations at a receptor well are much longer for landfills (hundreds or thousands of years) than for surface impoundments (most less than 100 years).

For humans exposed via the groundwater-to-surface-water (fish consumption) pathway, unlined and clay-lined surface impoundments posed risks above the HQ criterion and an excess cancer risk of 1 in 100,000 at the 90th percentile (see **Table ES-5**). For CCW managed alone in surface impoundments, these exceedences came from selenium (HQs of 3 and 2 for unlined and clay-lined units, respectively), while for CCW comanaged with coal refuse, these exceedences came from arsenic (3 in 100,000 and 2 in 100,000 excess cancer risks for unlined and clay-lined units, respectively). All 50th percentile surface impoundment risks are below an HQ of 1 and an excess cancer risk of 1 in 100,000. No constituents pose risks above these levels for landfills (including FBC landfills) at the 90th or 50th percentile.

Waste type has a much larger effect when managed in surface impoundments than when managed in landfills. In the case of surface impoundments, some constituents presented higher risks from CCW managed alone (boron, molybdenum, nitrate, and selenium). However, others presented higher risks when CCW is comanaged with coal refuse (arsenic, cadmium, cobalt, and lead).

The higher risks for surface impoundments than landfills are likely due to higher waste leachate concentrations and the higher hydraulic head from the impounded liquid waste. This is consistent with damage cases reporting wet handling as a factor that can increase risks from CCW management.

Table ES-1. Selected[a] 90th Percentile Risk Results by CCW Type: Landfills, Groundwater-to-Drinking-Water Pathway

Chemical	90th Percentile HQ or Cancer Risk Value[b]		
	Unlined Units	Clay-Lined Units	Composite-Lined Units
Conventional CCW – 79 landfills			
Cancer			
Arsenic III	4E-04	2E-04	0
Arsenic V	2E-04	3E-05	0
Noncancer			
Antimony	2	0.8	0
Molybdenum	2	0.8	0
Thallium	3	2	0
Codisposed CCW and Coal Refuse – 41 landfills			
Cancer			
Arsenic III	5E-04	2E-04	0
Arsenic V	4E-04	6E-05	0
Noncancer			
Molybdenum	2	0.6	0
Thallium	2	1	0
FBC Waste – 7 landfills			
Cancer			
Arsenic III	3E-05	6E-05	0
Arsenic V	2E-05	2E-05	0
Noncancer			
Antimony	0.8	3	0
Thallium	1	4	0

[a] Values are presented only for chemicals that exceed an excess cancer risk of 1 in 100,000 (arsenic only) or an HQ of 1.

[b] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000-year period of the analysis.

Table ES-2. Selected[a] 50th Percentile Risk Results by CCW Type: Landfills, Groundwater-to-Drinking-Water Pathway

Chemical	50th Percentile HQ or Cancer Risk Value[b]		
	Unlined Units	Clay-Lined Units	Composite-Lined Units
Codisposed CCW and Coal Refuse – 41 landfills			
Cancer			
Arsenic III	2E-05	6E-06	0

[a] Values are presented only for chemicals that exceed an excess cancer risk of 1 in 100,000 (arsenic only) or an HQ of 1.

[b] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000-year period of the analysis.

Table ES-3. Selected[a] 90th Percentile Risk Results by CCW Type: Surface Impoundments, Groundwater-to-Drinking-Water Pathway

Chemical	90th Percentile HQ or Cancer Risk Value[b]		
	Unlined Units	Clay-Lined Units	Composite-Lined Units
Conventional CCW – 44 surface impoundments			
Cancer			
Arsenic III	2E-03	9E-04	2E-07
Arsenic V	7E-04	2E-04	0
Noncancer			
Boron	7	4	5E-03
Lead (MCL)[c]	3	0.7	1E-21
Molybdenum	8	5	7E-03
Nitrate/nitrite (MCL)[c]	20	10	9E-04
Selenium VI	2	1	1E-03
Codisposed CCW and Coal Refuse – 72 surface impoundments			
Cancer			
Arsenic III	2E-02	7E-03	4E-06
Arsenic V	2E-02	2E-03	3E-09
Noncancer			
Cadmium	9	3	5E-05
Cobalt	500	200	3E-06
Lead (MCL)[c]	9	1	1E-19
Molybdenum	3	2	4E-03

[a] Values are presented only for chemicals that exceed an excess cancer risk of 1 in 100,000 (arsenic only) or an HQ of 1.

[b] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000-year period of the analysis.

[c] Values are ratios of exposure concentration to MCL.

Table ES-4. Selected[a] 50th Percentile Risk Results by CCW Type: Surface Impoundments, Groundwater-to-Drinking-Water Pathway

Chemical	50th Percentile HQ or Cancer Risk Value[b]		
	Unlined Units	Clay-Lined Units	Composite–Lined Units
Conventional CCW – 44 surface impoundments			
Cancer			
Arsenic III	1E-04	6E-05	0
Arsenic V	2E-05	4E-06	0
Codisposed CCW and Coal Refuse – 72 surface impoundments			
Cancer			
Arsenic III	6E-04	2E-04	0
Arsenic V	3E-04	4E-05	0
Noncancer			
Cobalt	20	6	0

[a] Values are presented only for chemicals that exceed an excess cancer risk of 1 in 100,000 (arsenic only) or an HQ of 1.

[b] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000-year period of the analysis.

Table ES-5. Selected[a] 90th Percentile Risk Results by CCW Type: Surface Impoundments, Groundwater-to-Surface-Water Pathway

Chemical	90th Percentile HQ or Cancer Risk Value[b]		
	Unlined Units	Clay-Lined Units	Composite-Lined Units
Conventional CCW – 44 surface impoundments			
Noncancer			
Selenium VI	3	2	2E-06
Codisposed CCW and Coal Refuse – 72 surface impoundments			
Cancer			
Arsenic III	3E-05	2E-05	1E-14
Arsenic V	2E-05	8E-06	6E-19

[a] Values are presented only for chemicals that exceed an excess cancer risk of 1 in 100,000 (arsenic only) or an HQ of 1.

[b] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000-year period of the analysis.

For ecological receptors exposed via surface water, risks for landfills exceeded an HQ of 1 for boron and lead at the 90th percentile, but 50th percentile HQs were well below 1. For surface impoundments, 90th percentile risks for several constituents exceeded the risk criteria, with boron showing the highest risks (HQ = 2,000). Only boron exceeded an HQ of 1 at the 50th percentile (HQ = 7). Exceedances for boron and selenium are consistent with reported ecological damage cases, which include impacts to waterbodies through the groundwater-to-surface-water pathway.

For ecological receptors exposed via sediment, 90th percentile risks for lead, arsenic, and cadmium exceeded the risk criteria for both landfills and surface impoundments because these constituents strongly sorb to sediments in the waterbody. The 50th percentile risks were generally an order of magnitude or more below the risk criteria.

Sensitivity analysis results indicate that for more than 70 percent of the scenarios evaluated, the risk assessment model was most sensitive to parameters related to the contaminant source and groundwater flow and transport, including WMU infiltration rate, leachate concentration, and aquifer hydraulic conductivity and gradient. For the groundwater-to-surface water pathway, another sensitive parameter is the flow rate of the waterbody into which the contaminated groundwater is discharging. For strongly sorbing contaminants (such as lead and cadmium), variables related to sorption and travel time are also important (adsorption coefficient, depth to groundwater, and receptor well distance).

Although the best available data and techniques were used, there were several uncertainties associated with the CCW risk assessment. The major types of uncertainty were as follows:

- **Scenario Uncertainty** includes the assumptions and modeling decisions that are made to represent an exposure scenario.
- **Model Uncertainty** is associated with all models used in a risk assessment because mathematical expressions are simplifications of reality that approximate real-world conditions and processes.
- **Parameter Uncertainty** occurs when there is a lack of data about the values used in the equations, data available are not representative of the instance being modeled, or parameter values have not been measured precisely because of limitations in technology.

Scenario uncertainty has been minimized by basing the risk assessment on conditions around existing U.S. coal-fired power plants around the United States. Uncertainty in environmental setting parameters has been incorporated into the risk assessment by varying these inputs within reasonable ranges when the exact value is not known. Uncertainty in human exposure factors (such as exposure duration, body weight, and intake rates) has also been addressed through the use of national distributions.

Some uncertainties not addressed explicitly in the risk assessment have been addressed through comparisons with other studies and data sources. These include the appropriateness of the leachate data used for landfills, concentrations of mercury in current CCW, and the potential impacts of future mercury regulations.

Other uncertainties are not as easily addressed as the ones above. These include issues such as receptor well distance, liner conditions, ecological benchmarks, ecological receptors at risk, and synergistic risks. Detailed discussion of all the risk

assessment uncertainties is presented in **Section 4.4** of the report.

Conclusions

Given the results and characterization above, composite liners, as modeled in this risk assessment, effectively reduced risks from all pathways and constituents below the risk criteria for both landfills and surface impoundments. The CCW risk assessment suggests that the management of CCW in unlined landfills and unlined surface impoundments may present risks to human health and the environment. Selenium in certain types of WMUs managing certain types of CCW may present a risk of clinical selenosis to highly exposed groundwater users or fish consumers, or a risk of adverse effects to highly exposed aquatic receptors. Arsenic in certain types of WMUs managing certain types of CCW may present lifetime cancer risks above EPA's range of concern to highly exposed groundwater users. Estimated risks from clay-lined units are lower than the risks of unlined units, but are still above the risk criteria used for this analysis. In addition, surface impoundments typically showed higher risks than landfills, regardless of liner type. Finally, for surface impoundments, codisposal of CCW with coal refuse results in significantly higher risks from arsenic and certain other constituents than CCW disposed alone, while for other constituents, managing CCWs alone results in higher estimated risks than codisposed CCW.

These risk results are in many cases consistent with damage cases compiled by EPA (U.S. EPA, 2000, 2003e, 2007) and others (Lang and Schlictmann, 2004; Zillmer and Fauble, 2004; Carlson and Adriano, 1993; Rowe et al., 2002; Hopkins et al., 2006).[7] For example, the full-scale modeling of selenium released from unlined surface impoundments into groundwater suggests that certain fish consumers may be exposed to relatively high levels of selenium, consistent with fish consumption advisories at some of the proven damage case sites. These results suggest that with a higher prevalence of composite liners in new CCW disposal facilities, along with practices to prevent codisposal of coal refuse with CCW, future national risks from onsite CCW disposal are likely to be lower than those presented in this risk assessment (which is based on 1995 CCW WMUs).

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[7] See **Sections 4.1.5** and **4.2.5** for a more complete discussion of CCW damage cases and risk assessment results.

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1.0 Introduction

1.1 Background

The U.S. Environmental Protection Agency (EPA) has evaluated the human health and environmental risks associated with coal combustion waste (CCW) management practices, including disposal in landfills and surface impoundments. In May 2000, EPA determined that regulation as hazardous wastes under Subtitle C of the Resource Conservation and Recovery Act (RCRA) was not warranted for certain CCWs, but that regulation as nonhazardous wastes under RCRA Subtitle D was appropriate. However, EPA did not specify regulatory options at that time. This risk assessment was designed and implemented to help EPA identify and quantify human health and ecological risks that may be associated with current management practices for high-volume CCWs. These wastes are fly ash, bottom ash, boiler slag, and flue gas desulfurization (FGD) sludge, along with wastes from fluidized-bed combustion (FBC) units and CCWs codisposed with coal refuse. This risk assessment will help EPA develop CCW management options for these high-volume waste streams. Details on EPA's CCW work can be found at http://www.epa.gov/epawaste/nonhaz/industrial/special/fossil/index.htm.

Note that the full-scale risk assessment described in this report was primarily conducted in 2003, meaning that the data collection efforts to support the risk assessment were based on the best information available to EPA at that time. As a result, more recent Agency efforts to characterize CCW wastes and management practices, such as the joint EPA and U.S. Department of Energy (DOE) survey of CCW waste management units (WMUs) (U.S. DOE, 2006) and EPA's recent study of CCW chemistries and leaching behavior (U.S. EPA, 2006c, 2008c), were not considered in the main analysis phase of this risk assessment. However, these more recent efforts are discussed as part of the risk characterization, and EPA is currently evaluating how to best incorporate and consider the results and findings of these studies in future efforts to address CCW management practices.

The Agency has revised this risk analysis document to address comments on the analytical methodology, data, and assumptions used in the risk assessment from an independent scientific peer review by experts outside EPA. Public comments (available in docket number EPA-HQ-RCRA-2006-0796[1]) were made available to the peer reviewers for their consideration during the review process. The peer review focused on technical aspects of the analysis, including the construction and implementation of the Monte Carlo analysis, the selection of models to estimate the release of constituents found in CCW from landfills and surface impoundments and their subsequent fate and transport in the environment, and the characterization of risks resulting from potential exposures to human and ecological receptors. EPA's responses to the peer-review comments, including descriptions of the revisions incorporated in this document to address those comments, are available in a separate response-to-comments document (U.S. EPA, 2009d).

[1] Available at http://www.regulations.gov.

1.2 Purpose and Scope of the Risk Assessment

The purpose of this risk assessment was to identify CCW constituents, waste types, exposure pathways, and receptors that may produce risks to human and ecological health, and to provide information about those scenarios that EPA could use to develop management options for CCW management.

The scope of this risk assessment was utility CCWs managed onsite at utility power plants. EPA's *Report to Congress: Wastes from the Combustion of Fossil Fuels* (U.S. EPA, 1999a) reports that there are 440 coal-fired utility power plants in the United States. Although these plants are concentrated in the East, they are found in nearly every state, with facility settings ranging from urban to rural. The large volumes of waste generated by these plants are typically managed onsite in landfills and surface impoundments. This risk assessment was designed to develop national human and ecological risk estimates that are representative of onsite CCW management settings throughout the United States.

1.3 Overview of Risk Assessment Methodology

To estimate the risks posed by the onsite management of CCW, this risk assessment estimated the release of CCW constituents from landfills and surface impoundments, the concentrations of these constituents in groundwater and surface water near coal-fired utility power plants, and the risks that these concentrations pose to human and ecological receptors.

1.3.1 Contaminant Sources

The size, design, and locations of the onsite CCW landfills and surface impoundments modeled in this risk assessment were based on data from a national survey of utility CCW disposal conducted by the Electric Power Research Institute (EPRI) in 1995 (EPRI, 1997). Data from this survey on facility area, volume, and liner characteristics were used in the CCW risk assessment because they were the most recent and complete data set available at the time the risk assessment was conducted (2003). However, as shown in **Table 1-1**, the EPA/DOE study conducted since then (U.S. DOE, 2006) shows a much higher proportion of lined facilities than do the 1995 EPRI data (see further discussion in **Section 4.4.1**).

Table 1-1. Liner Prevalence in EPRI and DOE Surveys

Liner Type	Landfills	Surface Impoundments
1995 EPRI Survey[a] – 181 facilities		
Unlined	40%	68%
Lined (compacted clay or composite [clay and synthetic])	60%	32%
2004 DOE Survey[b] – 56 facilities		
Unlined	3%	0%
Lined (compacted clay or composite [clay and synthetic])	97%	100%

[a] EPRI (1997)
[b] U.S. DOE (2006)

1.3.2 Exposure Pathways

The releases, and hence media concentrations and risk estimates in this report, were based on leaching to groundwater and groundwater transport to nearby wells and surface water bodies. This analysis did not address direct releases to surface water, which are permitted under the National Pollutant Discharge Elimination System (NPDES) of the Clean Water Act. Thus, the estimated media concentrations and risks do not take into account contributions from NPDES-permitted releases, including discharges due to flooding or heavy rainfall. Uncertainties associated with this decision are described in **Section 4.4.1** of this report.

EPA recognizes that there are exposure pathways in addition to the groundwater pathways addressed in this report that could be of concern to human health and ecological receptors, including fugitive dust eroded and transported by wind from uncovered CCW landfills, and erosion and transport of CCW constituents from uncovered landfills onto adjacent land and eventually into downslope waterbodies. These "aboveground" pathways were addressed in the 1998 risk assessment, and in 2002, EPA conducted a draft screening analysis (U.S. EPA, 2002a) to evaluate risks from these pathways.

1.3.3 Risk Levels

To evaluate the significance of the estimated risks from the pathways assessed in this assessment, EPA compared the risk estimates to a risk range (for carcinogens) or to a specific risk criterion (for noncarcinogens) that are protective of human health and the environment:

- An estimate of the excess lifetime cancer risk for individuals exposed to carcinogenic (cancer-causing) contaminants ranging from 1 chance in 1,000,000 (10^{-6} excess cancer risk) to 1 chance in 10,000 (10^{-4} excess cancer risk). For decisions made to screen out certain constituents from further consideration, a 1 in 100,000 (10^{-5}) excess lifetime cancer risk was used.[2]

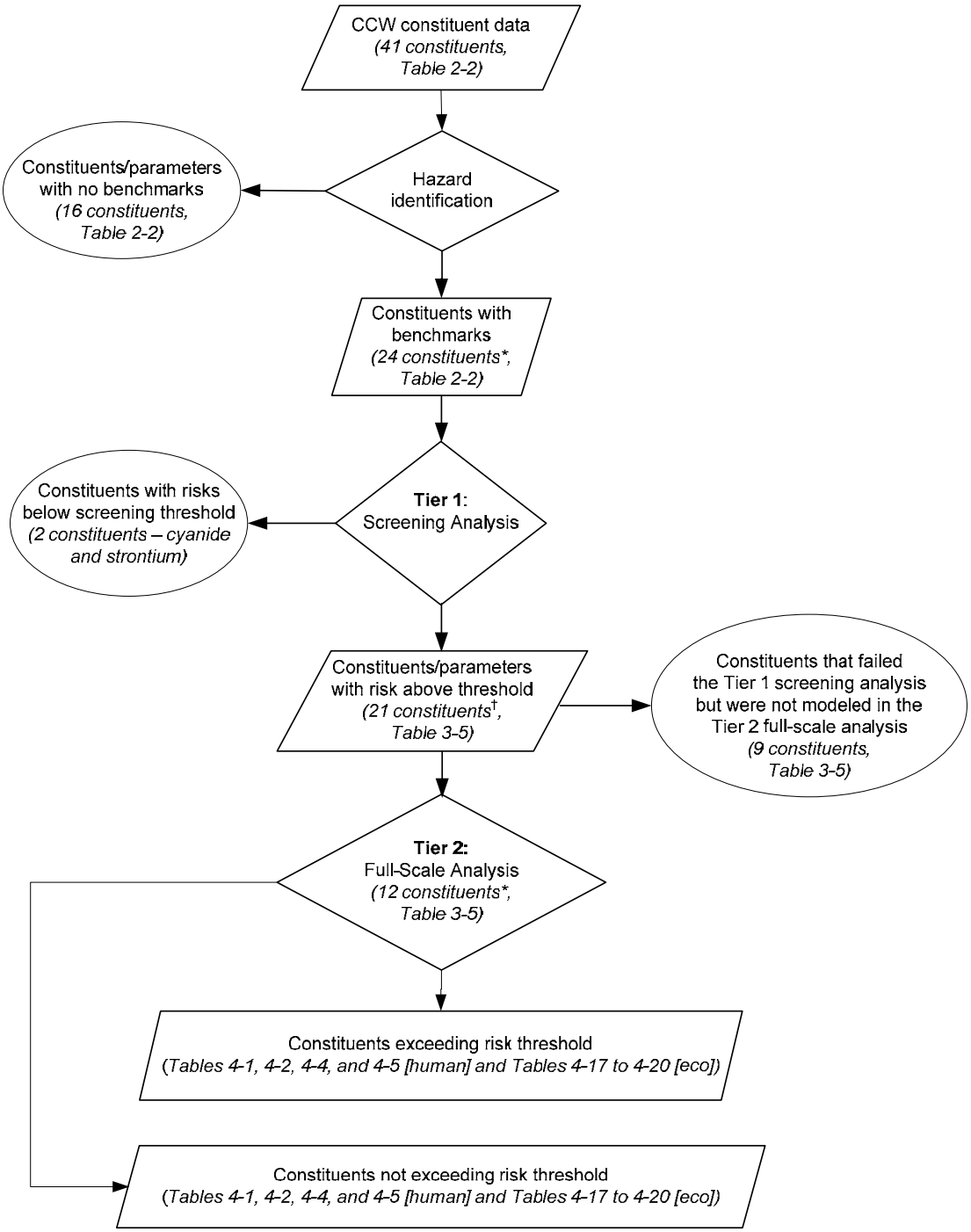
- A measure of safe intake levels to predicted intake levels, a hazard quotient (HQ) greater than 1 for constituents that can produce noncancer human health effects (an HQ of 1 is defined as the ratio of a potential exposure to a constituent to the highest exposure level at which no adverse health effects are likely to occur)

- An HQ greater than 1 for constituents with adverse effects to ecological receptors.

1.3.4 Methodology

In 1998, EPA conducted a risk assessment for fossil fuel combustion wastes (which include CCWs) to support the May 2000 RCRA regulatory determination (U.S. EPA, 1998a,b). Since then, EPA has added to the waste constituent database that was used in that effort, expanding the number of leachate and total waste analyses for 41 CCW constituents. The CCW risk assessment subjected these waste and leachate constituent concentrations to the tiered risk assessment methodology illustrated in **Figure 1-1**.

[2] The typical cancer risk range used by the Office of Solid Waste and Emergency Response is 10^{-4} to 10^{-6}.



* Does not include ammonia. Although ammonia was detected in CCW, data were insufficient to address it in the screening analysis or the full-scale analysis.

† Does not include mercury. Although mercury was considered in the screening analysis and modeled in the full-scale analysis, the results were not meaningful due to the high proportion of non-detect measurements.

Note: The risk threshold used for cancer risks was 1 in 100,000.

Figure 1-1. Overview of coal combustion waste risk assessment.

This methodology implemented the following steps to assess the human and ecological risk of CCWs:

- **Hazard Identification**, which collected existing human health and ecological benchmarks for the CCW constituents. Only constituents with benchmarks moved on to the next step, constituent screening.
- **Constituent Screening**, which compared very conservative estimates of exposure concentrations (e.g., using leachate concentrations) to health-based concentration benchmarks to quickly and simply identify constituents with risks below the screening criteria.
- **Full-Scale Analysis**, which characterized at a national level the human health and ecological risks for constituents in CCW disposed onsite in landfills and surface impoundments using a site-based probabilistic Monte Carlo risk analysis.

This document focuses on the full-scale Monte Carlo analysis, but includes a discussion of the hazard identification and screening analysis (in U.S. EPA, 2002a) that led to the full-scale assessment.

1.3.5 Waste Management Scenarios Addressed

The full-scale analysis was designed to characterize waste management scenarios based on two waste management options (disposal of CCW onsite in landfills and in surface impoundments) and three waste types, as follows:

- **Conventional CCW**, which includes fly ash, bottom ash, boiler slag, and FGD sludge
- **Codisposed CCWs and coal refuse,**[3] which are more acidic than conventional CCWs due to sulfide minerals in the mill rejects
- **FBC wastes**, which include fly ash and the fluidized bed ash, and which tend to be more alkaline than conventional CCW because of the limestone mixed in during fluidized bed combustion.

Conventional CCW and codisposed CCW and coal refuse are typically disposed of in landfills and surface impoundments that can be lined with clay or composite liners. FBC wastes are only disposed of in landfills in the United States; therefore, surface impoundment disposal was not modeled for FBC waste.

These three waste types, two waste management options, and three liner conditions (unlined, clay lined, composite lined) modeled in this analysis provide a good representation of CCW disposal practices and waste chemistry conditions that affect the release of CCW constituents from WMUs.

[3] Coal refuse is the waste coal produced from coal handling, crushing, and sizing operations, and tends to have a high sulfur content and low pH from high amounts of sulfide minerals (like pyrite). In the CCW constituent database, codisposed coal refuse includes “combined ash and coal gob,” “combined ash and coal refuse,” and “combined bottom ash and pyrites.”

1.3.6 Modeling Approach

The full-scale analysis was implemented using a site-based probabilistic approach that produces a distribution of risks or hazard for each receptor by allowing the values of some of the parameters in the analysis to vary. Input parameters were varied in the analysis using data collected at or around CCW disposal facilities or, when site-based data were not available, from distributions representing the variability of parameters across the United States. This approach was ideal for this risk assessment because there are many CCW facilities across the United States, and site-based data collection can capture both the variability in waste management practices at these facilities and the differences in their environmental settings (e.g., hydrogeology, climate, hydrology).

This probabilistic approach was implemented through seven primary steps:

Problem Formulation

1. Characterize the CCW constituents and waste chemistry, along with the size and liner status of the WMUs in which each waste stream may be managed

2. Characterize the environmental settings for the sites where CCW landfills and surface impoundments are located

3. Identify scenarios under which contaminants are released from a WMU and transported to a human receptor

Analysis

4. Screen risks to select CCW constituents for full-scale analysis

5. Predict the fate and transport of constituents in the environment once they are released from the WMUs at each site

6. Quantify the exposure of human and ecological receptors to the contaminant in the environment and the risk associated with this exposure

Risk Characterization

7. Estimate the risk to receptors from the exposure and characterize this risk in terms of exposure pathways, health effects, and uncertainties

8. Identify the waste disposal scenarios and environmental conditions that pose risks of potential concern to human health or the environment. Evaluate risks at the 50th and 90th percentiles.

1.4 Document Organization

This document is organized into the following sections:

- **Section 2, Problem Formulation,** describes how the framework for the full-scale analysis was developed, including identification of the waste constituents, exposure pathways, and receptors of concern; selection and characterization of waste management practices and sites to model; and development of the conceptual site models for the modeling effort.
- **Section 3, Analysis,** describes the probabilistic modeling framework and the models and methods used to (1) screen CCW constituents for the full-scale analysis, (2) estimate constituent releases from CCW landfills and surface impoundments (source models), (3) model constituent concentrations in the environmental media of concern (groundwater and surface water), (4) calculate exposure, and (5) estimate risk to human and ecological receptors.
- **Section 4, Risk Characterization,** characterizes the human health and environmental risks posed by CCW, including (1) discussion of the methods used to account for variability and uncertainty and (2) identification of the scenarios and conditions modeled that resulted in higher and lower risks. Results are presented as national estimates for CCW landfills and CCW surface impoundments, as well as by waste type and liner status. This section characterizes the risks posed by CCW constituents and pathways under the conditions modeled, including factors (such as liners or facility environmental setting) that result in higher or lower risk levels. Finally, the risk characterization evaluates the risk results in light of more recent research on CCW waste management practices and the environmental behavior of CCW constituents.

The first three appendices provide detailed information on how wastes, WMUs, and settings were characterized for the risk assessment. **Appendix A** describes the chemical characteristics of CCW, including the CCW leachate concentration distributions used to represent disposal conditions in landfills and surface impoundments. **Appendix B** describes how EPA characterized the CCW landfills and surface impoundments, including locations, surface area, capacities, geometry, and liner status. **Appendix C** presents the methodologies and data used to characterize the environmental setting at each CCW site identified in Appendix B, including delineating the site layout and determining the environmental setting (e.g., meteorology, climate, soils, aquifers, and waterbodies).

The next five appendices provide detailed information on the specific models and data used to calculate risk, including the nonlinear sorption isotherms (**Appendix D**), the surface water fate and transport and intake equations (**Appendix E**), the exposure factors (**Appendix F**), benchmarks for human health (**Appendix G**), and benchmarks for ecological risk (**Appendix H**).

The next three appendices provide background and results for the screening analysis, including calculation of health-based numbers (HBNs, **Appendix I**), chemical-specific inputs used in the screening analysis (**Appendix J**), and the screening analysis results (**Appendix K**).

Finally, **Appendix L** provides figures showing, for selected CCW constituents, cumulative percentiles of the time it took for the peak concentration to reach a receptor well for each source type.

2.0 Problem Formulation

The CCW risk assessment was intended to evaluate, at a national level, risk to individuals who live near WMUs used for CCW disposal. This section describes how the conceptual framework for the full-scale risk assessment was developed, including

- Constituent selection to identify the CCW constituents, exposure pathways, and receptors to address in this analysis (**Section 2.1.1**)
- Location and characterization of the CCW landfills and surface impoundments to be modeled as the sources of CCW contaminants in the full-scale site-based analysis (**Section 2.1.2**)
- The conceptual site model used to represent CCW disposal facilities (**Section 2.2**)
- The general modeling approach and scope, including constituent screening (**Section 2.3**), and full-scale modeling (**Section 2.4**) to estimate exposure point concentrations, assess exposures, and calculate risks to human and environmental receptors.

2.1 Source Characterization

The main technical aspects of the CCW risk assessment were completed in 2003, and the waste management scenarios modeled in this assessment were based on the best data on waste compositions, industry operations, and waste management practices that were available at that time. These data sources included a 1995 industry survey on CCW management practices (the EPRI comanagement survey [EPRI, 1997]) and data collected from a variety of sources before the 2003 risk assessment (e.g., EPA's CCW constituent database). Since 2003, DOE and EPA have completed a survey to characterize CCW waste disposal practices from 1994 to 2004, with a focus on new facilities or facility expansions completed within that same time frame (U.S. DOE, 2006). In addition, EPA studies of CCW composition and leaching behavior are ongoing (U.S. EPA, 2006c, 2008c). Although these newer data were not available when this risk assessment was conducted, they are discussed in the risk characterization (**Section 4**) as an uncertainty with respect to how well the risk assessment represents CCW leachate composition and current WMU liner conditions.

This risk assessment provides a national characterization of waste management scenarios for wastes generated by coal-fired utility power plants. The sources modeled in these scenarios are onsite landfills and surface impoundments, which are the primary means by which CCW is managed in the United States. The characterization of these sources, in terms of their physical dimensions, operating parameters, location, environmental settings, and waste characteristics, is fundamental to the construction of scenarios for modeling. This section describes how the coal combustion waste streams and management practices were characterized (based on the above

data sources) and screened to develop the waste disposal scenarios modeled in the full-scale analysis.

2.1.1 Identification of Waste Types, Constituents, and Exposure Pathways

To identify the CCW constituents and exposure pathways to be addressed in this risk assessment, we relied on a database of CCW analyses that EPA had assembled over the past several years to characterize whole waste and waste leachate from CCW disposal sites across the country (see **Appendix A**). The 2003 CCW constituent database includes all of the CCW characterization data used by EPA in its previous risk assessments, supplemented with additional data collected from public comments, data from EPA Regions and state regulatory agencies, industry submittals, and literature searches up to 2003.

The CCW constituent database represents a significant improvement in the quantity and scope of waste characterization data available from the 1998 EPA risk assessment of CCWs (U.S. EPA, 1998a,b). For example, the constituent data set used for the previous risk assessments (U.S. EPA, 1999a) covered approximately 50 CCW generation and/or disposal sites, while the 2002 CCW constituent database covers approximately 140 waste disposal sites.[1] The 2002 database also has broader coverage of the major ion concentrations of CCW leachate (e.g., calcium, sulfate, pH), that can influence CCW impacts on human health and the environment.

2.1.1.1 Waste Types

Table 2-1 shows the waste types included in the 2002 CCW constituent database, along with counts of the number of sites with wastes of each type with constituent measurements in landfill leachate, surface impoundment porewater, and whole waste.

Comments received by EPA on the previous CCW risk assessment pointed out that the analysis did not adequately consider the impacts of CCW leachate on the geochemistry and mobility of metal constituents in the subsurface. Commenters stated that given the large size of the WMUs and the generally alkaline nature of CCW leachate, it is likely that the leachate affects the geochemistry of the soil and aquifers underlying CCW disposal facilities, which can impact the migration of metals in the subsurface. To address this concern, EPA statistically evaluated major ion porewater data from the CCW constituent database for the waste streams shown in Table 2-1. Based on this analysis and prevalent comanagement practices, EPA grouped the waste streams into three statistically distinct categories: conventional CCW (fly ash, bottom ash, slag, and FGD sludge), which has moderate to high pH; codisposed CCW and coal refuse, which tends to have low pH; and FBC waste, which tends to have high pH. As shown in Table 2-1, each of these waste types included several waste streams that are usually codisposed in landfills or surface impoundments. Note that some sites in the CCW database have more than one waste stream, so the site counts for the different waste streams in a waste type category sum to more than the total site count for that waste type.

[1] Although EPA believes that the 140 waste disposal sites do represent the national variability in CCW characteristics, they are not the same sites as in the EPRI survey. During full-scale modeling, data from the CCW constituent database were assigned to each EPRI site based on the waste types reported in the EPRI survey data.

Table 2-1. Waste Streams in CCW Constituent Database

Waste Type Waste Stream	Landfills		Surface Impoundments
	Landfill Leachate	**Total Waste[b]**	**Pore Water**
Conventional CCW	***97***	***62***	***13***
Ash (not otherwise specified)	43	30	0
Fly ash	61	33	2
Bottom ash and slag	24	23	3
Combined fly and bottom ash	7	4	4
FGD sludge	4	5	6
Codisposed Ash & Coal Refuse	***9***	***1***	***5***
FBC Waste	***58***	***54***	***0***
Ash (not otherwise specified)	18	10	0
Fly ash	33	32	0
Bottom and bed ash	26	25	0
Combined fly & bottom ash	20	22	0

[a] For waste types (shaded rows) the table gives the number of sites; for waste streams (unshaded rows), the table gives the number of samples.
[b] Whole waste concentration data.

Along with the type of WMU (landfill or surface impoundment), the three waste types in Table 2-1 defined the basic modeling scenarios to be addressed in the full-scale analysis. To characterize these waste types, the CCW constituent database was queried by waste type to develop the waste concentration data for the constituents and the major ion and pH conditions used to develop waste-type-specific metal sorption isotherms (see **Appendix D** for a more extensive discussion of the development of CCW waste chemistries and metal sorption isotherms).

2.1.1.2 CCW Constituents of Potential Concern

The CCW constituent database contains data on more than 40 constituents. During the hazard identification step of the CCW risk assessment, constituents of potential concern were identified from this list of constituents by searching EPA and other established sources for human health and ecological benchmarks (e.g., Agency for Toxic Substances and Disease Registry [ATSDR]; see **Section 3.1** and **Appendices G** and **H** for a full list of sources). **Table 2-2** shows the results of that search for each constituent. Benchmarks were found for 24 chemicals in the constituent database. The 16 constituents without human health or ecological benchmarks were not addressed further in the risk analysis.[2]

[2] The CCW constituents without human health benchmarks are limited to common elements, ions, and compounds (e.g., iron, magnesium, phosphate, silicon, sulfate, sulfide, calcium, pH, potassium, sodium, carbon, sulfur). These measurements were used to determine overall CCW chemistries modeled in the risk assessment (see Section 3). Although some of these chemicals or parameters (e.g., pH, sulfate, phosphate, chloride) can pose an ecological hazard if concentrations are high enough, they were not addressed in this risk assessment.

Table 2-2. Toxicity Assessment of CCW Constituents

Constituent	CAS ID	HHB[a]	EcoB[b]
Metals			
Aluminum	7429-90-5	✔	✔
Antimony	7440-36-0	✔	✔
Arsenic	7440-38-2	✔[c]	✔
Barium	7440-39-3	✔	✔
Beryllium	7440-41-7	✔[d]	✔
Boron	7440-42-8	✔	✔
Cadmium	7440-43-9	✔[d]	✔
Chromium	7440-47-3	✔[c]	✔
Cobalt	7440-48-4	✔	✔
Copper	7440-50-8	✔	✔
Iron	7439-89-6		
Lead	7439-92-1	✔[e]	✔
Magnesium	7439-95-4		
Manganese	7439-96-5	✔	
Mercury	7439-97-6	✔	✔
Molybdenum	7439-98-7	✔	✔
Nickel	7440-02-0	✔	✔
Selenium	7782-49-2	✔	✔
Silver	7440-22-4	✔	✔
Strontium	7440-24-6	✔	
Thallium	7440-28-0	✔	✔
Vanadium	7440-62-2	✔	✔
Zinc	7440-66-6	✔	✔
Inorganic Anions			
Chloride	16887-00-6		
Cyanide	57-12-5	✔	
Fluoride	16984-48-8	✔	
Nitrate/nitrite	14797-55-8/14797-65-0	✔	
Phosphate	14265-44-2		
Silicon	7631-86-9		
Sulfate	14808-79-8		
Sulfide	18496-25-8		
Inorganic Cations			
Ammonia	7664-41-7	✔	
Calcium	7440-70-2		
pH	12408-02-5		
Potassium	7440-09-7		
Sodium	7440-23-5		
Nonmetallic Elements			
Carbon	7440-44-0		
Sulfur	7704-34-9		

(continued)

Toxicity Assessment of CCW Constituents (continued)

Constituent	CAS ID	HHB[a]	EcoB[b]
Measurements			
Total Dissolved Solids	none		
Total Organic Carbon	none		
Dissolved Organic Carbon	none		

[a] HHB = human health effect benchmark
[b] EcoB = ecological benchmark
[c] Known carcinogen (for chromium VI, inhalation only); although arsenic can act as both a carcinogen and a noncarcinogen, the cancer risk exceeds the noncancer risk at any concentration, so the more protective cancer benchmark for human health was used throughout this assessment.
[d] Probable carcinogen
[e] Safe Drinking Water Act Action Level only

2.1.2 Waste Management Scenarios

The full-scale CCW risk assessment modeled landfills and surface impoundments managing wastes onsite at coal-fired utility power plants. Because EPA selected a site-based modeling approach for the full-scale analysis, it was necessary to locate these disposal sites across the country to provide the spatial foundation for this analysis. It was also necessary to characterize CCW WMUs to define the scope for source modeling.

Two primary sources of data on these were used to characterize this population:

- 1998 Energy Information Agency (EIA) data on coal-fired power plants, which identifies approximately 300 coal-fired power plants with onsite waste management
- The 1995 EPRI waste comanagement survey (EPRI, 1997), which contains detailed WMU data (i.e., area, capacity, liner status, and waste type) for 177 of those facilities.

Because of the completeness of the WMU data from the EPRI survey, the EPRI data were used to establish the plant locations and WMU data for the full-scale modeling effort for conventional CCW[3] and CCW codisposed with coal refuse, as well as to help define protective waste management settings for the screening analysis.

Note that although there is overlap, the 140-site CCW constituent database described in Appendix A and the EPRI survey used to characterize CCW landfills and surface impoundments were assembled under separate efforts and represent different populations of disposal sites. As described in Section 3.1.3, these data sets were sampled independently during the Monte Carlo analysis, and constituent data were not assigned to particular sites except by waste type.

Although there is a good amount of FBC data in the constituent database (58 sites; see Table 2-1), there were only 3 FBC landfill sites in the EPRI database and 4 additional sites added by EPA, for a total of 7 FBC sites with data on onsite WMUs. Because EPA believes that this

[3] Fly ash, bottom ash, boiler slag, and FGD sludge.

small sample is not sufficient to represent the universe of FBC disposal units and, if included in the overall analysis, could bias the Monte Carlo results towards the environmental conditions around these few landfill units, FBC wastes were addressed separately from the more conventional CCW types in the full-scale analysis and are not included with the conventional and codisposal CCW management scenarios in the overall results. **Section 4.1.3** compares the risk results for each of these waste types, including FBC.

Table 2-3 shows how the plants were distributed across the waste type/WMU scenarios modeled in the full-scale analysis. The distribution across the waste type/WMU scenarios, the geographic distribution of these facilities, and the size and liner status of the WMUs were assumed to be representative of all onsite CCW landfills and surface impoundments in the continental United States as of 1995. As mentioned previously, DOE and EPA have conducted a newer survey on CCW disposal facilities (U.S. DOE, 2006), but the scope of this survey was not as comprehensive as the EPRI survey (e.g., WMU areas and capacity data were not collected). Newer information (U.S. DOE, 2007a,b) suggest that there now may be up to approximately 500 coal-fired electric utility power plants in the United States, the majority of which would be expected to conduct some waste management activities in onsite landfills or surface impoundments (U.S. EPA, 2010).

Table 2-3. Coal Combustion Plants with Onsite CCW WMUs Modeled in the Full-Scale Assessment

Waste Type and Liner Status	Number of Plants in 1995 EPRI Survey[a] with Onsite:		
	Landfills	Surface Impoundments	Either WMU Type[b]
Conventional CCW[c]	71	38	103
unlined	*38*	*24*	*60*
clay-lined	*28*	*10*	*38*
composite-lined	*10*	*5*	*15*
Codisposed CCW and coal refuse	38	65	100
unlined	*20*	*52*	*69*
clay-lined	*10*	*11*	*21*
composite-lined	*9*	*2*	*11*
FBC waste[d]	7	-	7
unlined	*3*		*3*
clay-lined	*3*		*3*
composite-lined	*1*		*1*
All waste types	108	96	181

[a] EPRI (1997); note that some coal combustion plants have one or more onsite WMUs.
[b] Number of coal combustion plants with onsite landfill(s), surface impoundment(s), or both.
[c] Fly ash, bottom ash, boiler slag, and FGD sludge.
[d] Includes 3 EPRI Survey FBC landfills plus 4 additional FBC landfills added by EPA. FBC was treated separately in the full-scale assessment because of the small number of FBC sites.

2.2 Conceptual Model

The waste stream/WMU combinations discussed above provided the waste management scenarios evaluated in the risk assessment. The full-scale assessment used the EPRI survey data to place these scenarios at actual onsite CCW disposal sites across the country. These sites were

used as the basis for a national-scale site-based Monte Carlo assessment of risks posed by the onsite disposal of CCW at utility power plants across the United States. **Figure 2-1** maps the CCW disposal sites modeled in this analysis against long-term average precipitation levels for the country.

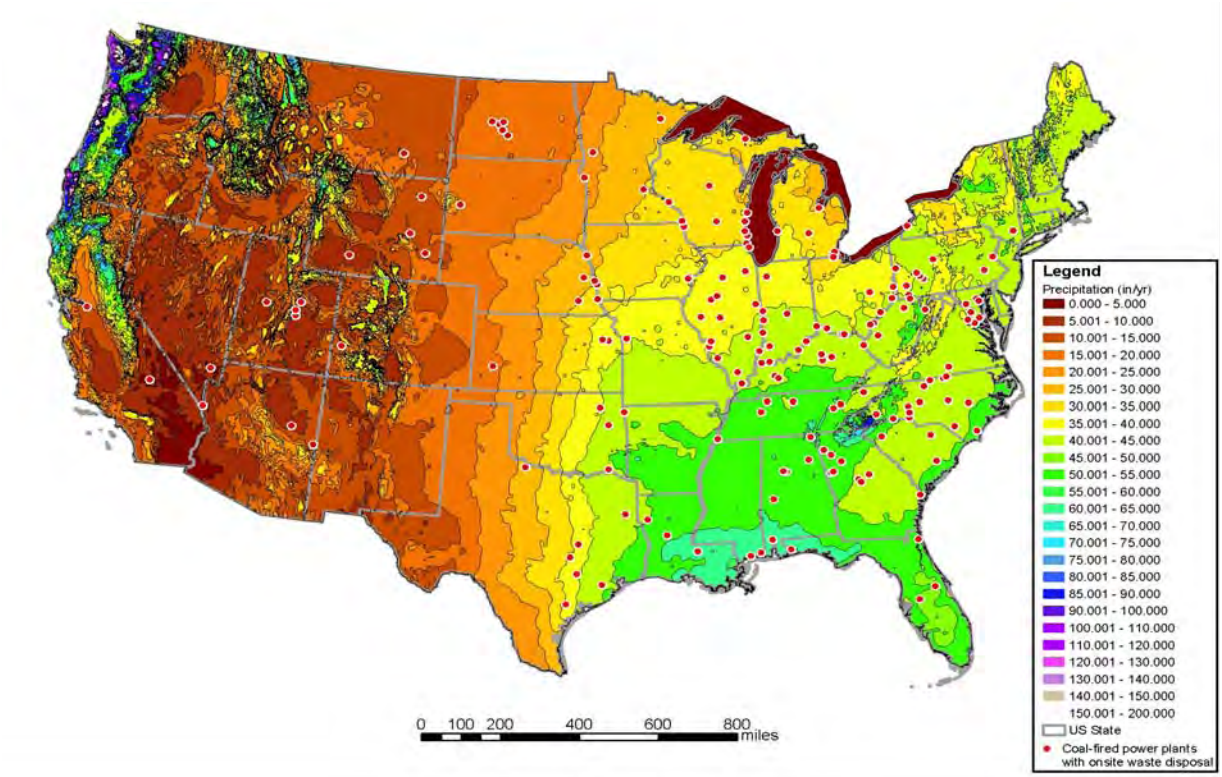


Figure 2-1. Coal combustion plants with onsite waste disposal modeled in CCW risk assessment.

2.2.1 Conceptual Site Model

Figure 2-2 depicts the conceptual site model for CCW disposal that was the basis for the national CCW risk assessment, including contaminant sources, exposure pathways, and receptors. The CCW conceptual site model includes the following exposure pathways:

Human Health:

- Groundwater to drinking water (drinking water ingestion)
- Groundwater to surface water (fish consumption)

Ecological Risk:

- Groundwater to surface water and subsequent direct contact with contaminated surface water and sediments
- Groundwater to surface water and subsequent ingestion of contaminated aquatic food items.

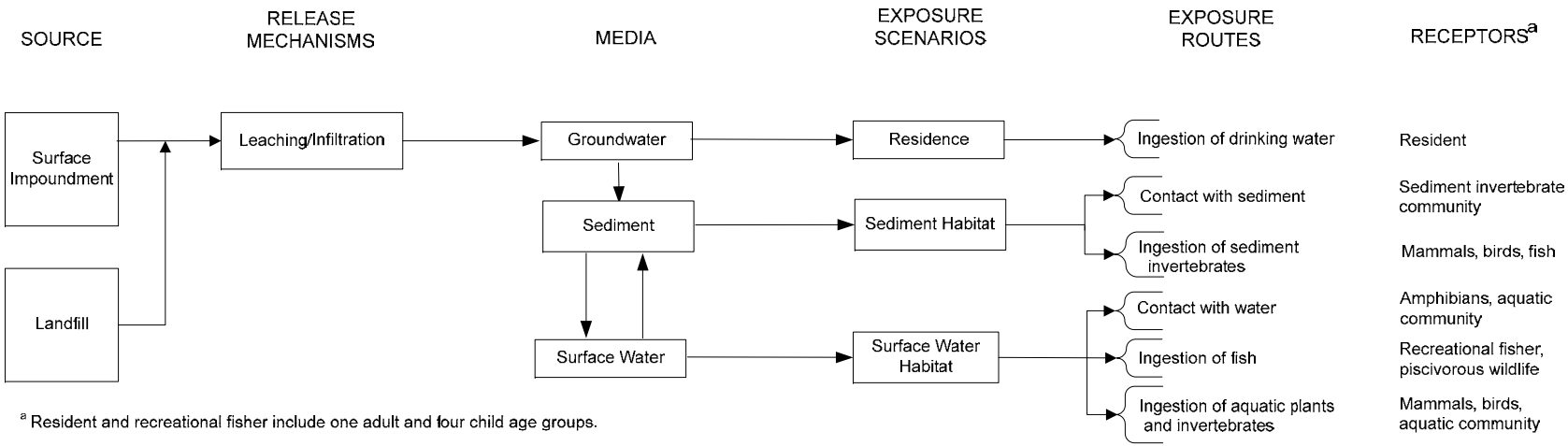


Figure 2-2. Conceptual site model of CCW risk assessment.

As shown in Figure 2-2, EPA focused full-scale modeling on groundwater-to-drinking-water and groundwater-to-surface-water exposure pathways for the national risk assessment. This groundwater pathway analysis evaluated exposures through drinking water ingestion and surface water contamination from groundwater discharge. For the groundwater-to-surface-water pathway, the analysis assumed that human exposure occurs through the consumption of contaminated fish and that ecological exposure occurs through direct contact with contaminated surface water and sediment or from the consumption of aquatic organisms.

2.2.2 Conceptual Site Layouts

This risk assessment was based on site layouts that are conceptual rather than site-specific. Although EPA had plant locations and some site-specific data on WMUs, we did not have the exact locations of each WMU or the residential wells surrounding each facility. Therefore, EPA had to develop conceptual layouts to place receptors around each WMU.

The conceptual site layouts capture possible relationships between a WMU and human and ecological receptors by locating, with respect to the WMU boundary, the geographic features (i.e., receptor wells, waterbodies) that are important for determining human and ecological exposures to chemicals released from CCW landfills and surface impoundments.

Two site layouts were used in the full-scale analysis to model the land use scenarios of most concern for CCW disposal facilities:

- Residential groundwater ingestion scenario
- Recreational fisher and aquatic ecological risk scenario.

These two conceptual site layouts are shown in the following two subsections, including WMU boundaries, waterbodies, and residential wells modeled in this analysis. In the conceptual site layouts, the WMU is represented as a square source. The size of the source was determined by the surface area of the WMU (CCW WMU areas were collected from the EPRI comanagement survey, as described in **Appendix B**). The WMU was assumed to be located at the property line of the facility to which it belongs.

Adjacent to the WMU is a buffer area within which there was assumed to be no human activity that would present human risk (i.e., there are no residences or waterbodies in the buffer). The buffer area lies between the WMU boundary and the residential well or waterbody, and represents the distance to well or waterbody discharge point modeled by the groundwater model. Each site layout must also be oriented in terms of direction.

2.2.2.1 Residential Groundwater-to-Drinking-Water Scenario

The residential groundwater-to-drinking-water scenario, shown in **Figure 2-3**, calculated exposure through residential use of well water as drinking water. In the Monte Carlo analysis, the receptor well was randomly placed up to 1 mile downgradient from the edge of the WMU (this radial well distance is labeled R_{rw} in Figure 2-3), based on a nationwide distribution of nearest downgradient residential wells from Subtitle D municipal landfills (U.S. EPA, 1988a; this distribution is provided in **Appendix C**). EPA assumed that this distribution was relevant to

onsite CCW landfills and surface impoundments at coal-fired utility power plants, but does not have data on typical distances (or the distributions of distances) of domestic drinking water wells from CCW disposal facilities. (The potential impact on the results of this assumption is discussed as an uncertainty in **Section 4.4.3.3**).

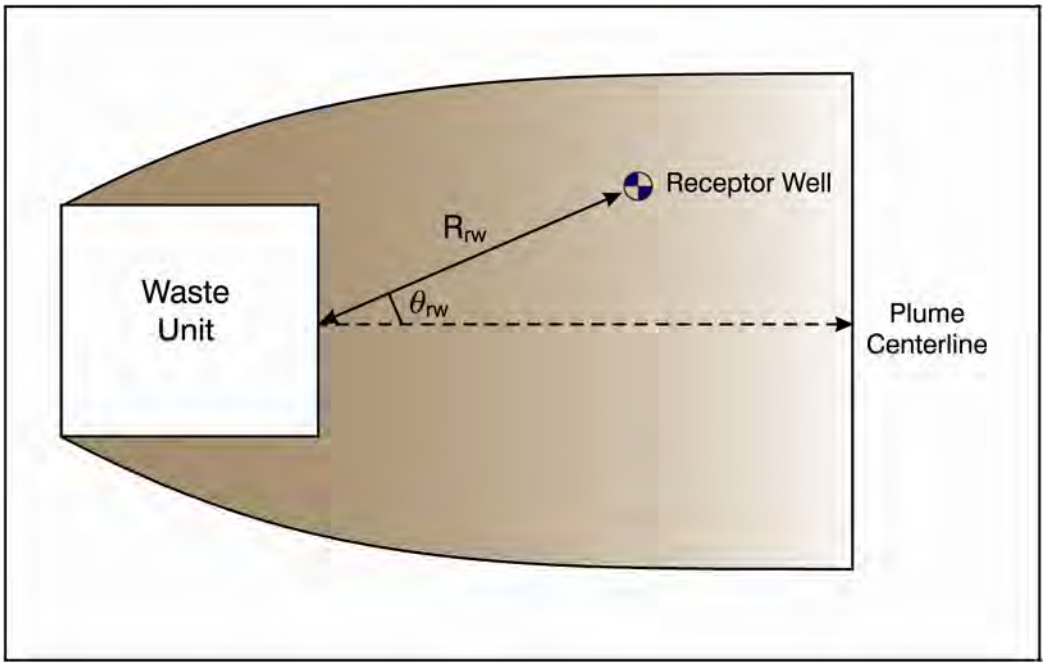


Figure 2-3. Conceptual site layout for residential groundwater ingestion scenario.

The angle off the contaminant plume centerline (θ_{rw} in Figure 2-3) was based on a uniform distribution ranging from 0 to 90°. The depth of the well below the water table was set within the groundwater model based on assumptions that are generally typical of average conditions for surficial aquifers across the United States. These limits are discussed in **Section 3.6.3**. In this assessment, receptors were always located within the lateral extent of the plume.

The soil and aquifer characteristics needed for the groundwater model were based on available data on soil and groundwater conditions collected around the 181 modeled sites, as described in **Appendix C**.

2.2.2.2 Recreational Fisher and Ecological Risk Scenario

The recreational fisher[4] scenario, shown in **Figure 2-4**, was used to estimate risks to recreational fishers (and their children) who live near the CCW landfills and surface impoundments and catch and consume fish from a waterbody located adjacent to the buffer and contaminated by CCW constituents through the groundwater to surface water pathway. The

[4] Only recreational fishers were considered as the reasonable maximum exposed individuals. Subsistence receptors who eat fish were not modeled, but could be expected to have higher risks than the recreational fishers for whom we present results.

potential for cumulative exposure from both contaminated fish and groundwater was not considered in the CCW risk assessment. One reason is that the exposures are likely to occur over different timeframes because of differences in transit time of the contaminant plume to wells versus surface waterbodies. As described in **Section 3.6.3**, for each model run in the Monte Carlo analysis, the distances to the downgradient well and surface water were independently sampled from national distributions presented in Appendix C, Tables C-1 (wells) and C-2 (surface waterbodies). Also, these exposures may involve different receptors because a resident exposed via groundwater may not be a recreational fisher. Thus, adding risks across pathways would not likely change the results.

The waterbody was assumed to be a stream or lake located downgradient from the WMU, beginning where the buffer area ends (see Figure 2-4), and was also used as the most impacted aquatic system for the ecological risk assessment. Waterbody characteristics were determined based on a combination of site-specific, regional, or national data (as described in **Appendix C**), except for the length of the stream impacted by the plume, which was determined by the width of the plume as it intersects the waterbody.

The downgradient distance to the surface water body was determined from a national distribution developed by measuring this distance (using scaled U.S. Geological Survey [USGS] maps and aerial photographs obtained from the Terraserver Web site [http://terraserver.usa.com/geographic.aspx]) at 59 CCW landfill and surface impoundment sites randomly selected from a larger data set of 204 CCW WMUs, including those modeled in this risk assessment. **Appendix C** presents that distribution and further details on how the distribution was developed and the sample of 59 facilities used to develop the distribution.

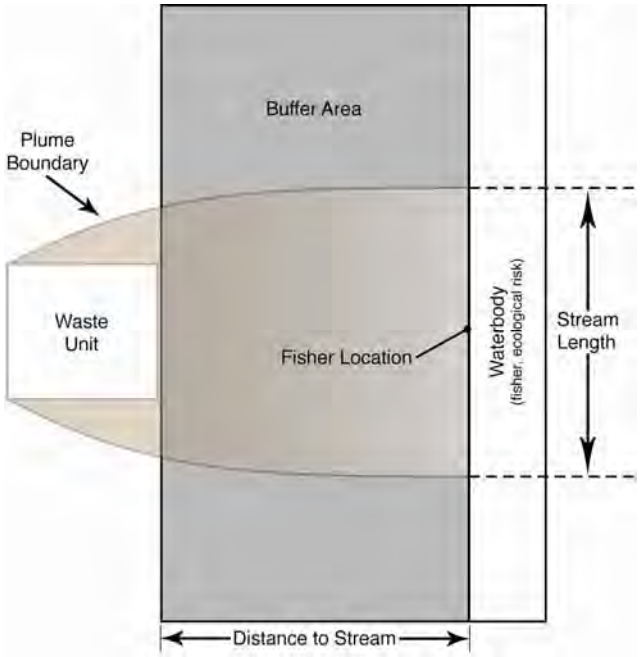


Figure 2-4. Conceptual site layout for residential fisher and aquatic ecological risk scenario.

2.3 Screening Analysis

To assist in selecting constituents for full-scale modeling, a screening analysis was conducted in 2002 (U.S. EPA, 2002a) that compared very conservative estimates of exposure concentrations (e.g., leachate concentrations) to health-based concentration benchmarks to quickly and simply identify constituents with risks that clearly do not exceed the risk criteria so that these could be eliminated from further analysis. For example, for the groundwater-to-drinking-water pathway, leachate concentrations were compared directly to drinking water standards, which is equivalent to assuming that human receptors are drinking leachate.[5] Similarly conservative estimates were used for ecological receptors (e.g., fish swimming directly in leachate). EPA made use of those screening results in this risk assessment, which was conducted in 2003 and documented in the August 6, 2007, draft report and its subsequent revisions, including the current document. **Section 3.2** provides further detail on how the CCW screening analysis was conducted to develop the list of CCW constituents modeled in the full-scale analysis.

2.4 Full-Scale Risk Assessment

Although the screening analysis identified the potential for risk for a subset of the constituents reported in CCW, the conservative assumptions used precluded an accurate quantitative estimate of these risks. The screening results were not intended to, and do not, characterize the risks that we expect would actually occur, because the purpose is not to characterize risks but rather to identify those constituent/pathway/receptor combinations that are unlikely to be problematic versus those that are most likely to be problematic. To gain a better understanding of the risks that may be posed by the constituents identified as likely to be problematic, EPA conducted a full-scale probabilistic (Monte Carlo) risk assessment to estimate the national distribution of the risks to human health and the environment posed by CCW disposal, and to provide the information needed to assess future management options for these wastes in the context of their risks to human health and the environment. The full-scale CCW Monte Carlo risk assessment was designed to characterize the national CCW risk profile in terms of WMU type, waste type, and constituent, and to use distributions in a probabilistic modeling framework to incorporate variability and uncertainty into the analysis.

The full-scale modeling approach used data about waste management practices and environmental conditions at 181 utility CCW disposal sites across the United States.[6] These sites were assumed to represent the universe of CCW onsite waste disposal sites at the time of the EPRI survey (1995) and defined the national framework for the risk assessment. One question related to this risk assessment is how CCW facilities may have changed since the 1995 EPRI survey. Although the DOE/EPA survey did not include all of the data needed to conduct a risk assessment (WMU area and capacity data were not collected), liner conditions were addressed, and by comparing the DOE/EPA survey results to the EPRI data, it is possible to assess how

[5] Note that RCRA waste disposal risk assessments do not address direct discharges from impoundments to surface waters because they are regulated as permitted point source discharges under the Clean Water Act by EPA's Office of Water.

[6] These 181 sites include177 sites from the EPRI survey and 4 additional CCW sites added by EPA to better represent FBC waste disposal facilities; see Section 2.1.2.

liner conditions have changed as CCW facilities were built or expanded since 1995. The 56 WMUs surveyed in the U.S. DOE (2006) study were commissioned between 1994 and 2004. Although the actual number of WMUs that were established in that timeframe cannot be verified, based on proxy data (i.e., CCW available for disposal in those states with identified new WMUs and coal-fired power plant generating capacity), the sample coverage was estimated to be at least 61 to 63 percent of the total population of the newly commissioned WMUs.[7] With the exception of one landfill, the newly constructed facilities are all lined, with either clay, synthetic, or composite liners. The single unlined landfill identified in the recent DOE report receives bottom ash, which is characterized as an inert waste by the state, and therefore, a liner is not required. There has been a marked trend away from unlined WMUs in favor of lined units, with a distinct preference for synthetic or composite liners. A comparison of the 26 coal combustion plants in both the EPRI survey and the DOE/EPA survey (U.S. DOE, 2006) showed that although most of those facilities (17 of 26) were using unlined WMUs in 1995, all 26 are now placing wastes in new or expanded landfills or surface impoundments that are lined with clay, synthetic, or composite liners. However, it is likely that the older unlined units were closed with wastes in place, and that these wastes therefore still pose a threat through groundwater pathways. In addition, the available data cannot be used to determine the number of unlined units that continue to operate in the United States. See further discussion of the uncertainty posed by the use of the EPRI liner data in **Section 4.4.1**.

The full-scale assessment was conducted using several modeling components: (1) EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP; U.S. EPA, 1997a) groundwater model, (2) a simple steady-state surface water and aquatic food web model, and (3) a multipathway exposure and risk modeling system.

2.4.1 Data Collection

For the sites representing each WMU and waste type combination selected for analysis, the Monte Carlo analysis began with input files that contain, for each Monte Carlo realization, the following variables collected at and around each of the 181 modeled sites:

- WMU area, depth, and capacity
- WMU liner status (no liner, clay liner, composite liner)
- Waste type (conventional CCW, CCW codisposed with coal refuse, FBC wastes)
- Soil texture (for vadose zone properties and infiltration rates)
- Soil pH and organic carbon
- Aquifer type
- Groundwater temperature
- Climate center (for infiltration rates)
- USGS Hydrologic Region (for surface water quality data)
- Surface water type and flow conditions.

[7] For additional details as to how these estimates were derived, the reader is referred to the DOE study, pages S-2 to S-3 of the Summary Section and Section 3.1.2.

Data sources and collection methods for these variables may be found in **Appendices B** and **C**.

CCW constituent data in the CCW constituent database were used as a national empirical distribution of the concentrations of the constituents of concern in CCW landfill leachate and surface impoundment porewater. Like the WMU database, the CCW constituent data include WMU type and waste type, which enabled constituent concentrations to be assigned to the 181 CCW sites by waste type and WMU type. The CCW constituent database was also used to assign (by waste type) the high, medium, and low leachate pH and ionic strength conditions needed to select the appropriate subsurface sorption isotherms for each model run (see **Appendix D**).

Because site-specific data were not readily available, national distributions were used to populate the following variables by model run:

- Distance to nearest drinking water well
- Distance to nearest surface waterbody
- Aquifer depth, thickness, gradient, and hydraulic conductivity (based on site-specific hydrogeologic setting)
- Soil hydrologic properties (based on site-specific soil type).

The data sources used to develop national distributions for these variables are described in **Appendix C**. Human exposure factors, such as exposure duration and drinking water and fish consumption rates, were also based on national distributions, which are provided in **Appendix F**.

2.4.2 Model Implementation

As a first step in the modeling process, the groundwater model (EPACMTP) read the site-based data files to estimate the following for each model run:

- Drinking water well peak concentration
- Time to drinking water peak concentration
- Peak surface water contaminant flux
- Time to peak surface water contaminant flux.

The groundwater model was run until contaminant concentrations at the receptor point returned to zero after the concentration peak or for the maximum simulation time of 10,000 years, whichever came first.

Groundwater model results were passed to the multimedia modeling system to estimate surface water and sediment concentrations and to calculate human and ecological exposure and risk. Additional inputs sent to the model at this stage included

- Site-based surface waterbody type, dimensions, flows, pH, and total suspended solids (TSS) concentration
- Chemical-specific fish bioconcentration factors (BCFs)
- Human exposure factors (from national distributions)
- Human and ecological health benchmarks.

For human health, the multimedia modeling system calculated risk from drinking water ingestion and fish consumption for each realization. For ecological risk, the model used surface water and sediment concentrations along with ecological benchmarks to estimate the risks to ecological receptors.

2.4.3 Exposure Assessment

Table 2-4 lists the human and ecological receptors considered in the CCW risk assessment, along with the specific exposure pathways that apply to each receptor. All of the receptors that EPA considered were assumed to live offsite, at a location near the WMU.

Table 2-4. Receptors and Exposure Pathways Addressed in the Full-Scale CCW Assessment

Receptor	Ingestion of Drinking Water	Fish Consumption	Direct Contact with Surface Water and Sediment	Ingestion of Aquatic Organisms
Human Receptors				
Adult resident	✔			
Child resident	✔			
Adult recreational fisher		✔		
Child recreational fisher		✔		
Ecological Receptors				
Aquatic and sediment organisms			✔	
Mammals and birds				✔

For human receptors, the exposure assessment estimated the dose to an individual receptor by combining modeled CCW constituent concentrations in drinking water or fish with intake rates for adult and child receptors. The full-scale CCW risk assessment considered exposures due to chemicals leaching from WMUs and contaminating groundwater. The groundwater exposures include drinking water ingestion and consumption of recreationally caught contaminated fish from surface waterbodies affected by contaminated groundwater. For the groundwater-to-drinking-water pathway, it was assumed that well water was the only source

of drinking water (although some households may drink bottled or treated water or may drink water outside the home, e.g., at work or at school).

For ecological receptors, exposure assumptions were incorporated into the development of ecological benchmarks (see **Appendix H**), which were surface water and sediment concentrations corresponding to an HQ of 1.

The time period for the exposure assessment was defined by the peak concentration in the media of concern and the exposure duration. For human receptors, annual average media concentrations were averaged over the randomly selected exposure duration around the peak concentration for each run. To protect against chronic effects to ecological receptors, EPA considered the exposure duration over a significant portion of the receptor's lifetime, and we believe that one year is the appropriate period of time for that. To be protective, we used the highest (peak) annual average concentration to estimate ecological exposure and risk.

2.4.4 Risk Estimation

Risk was estimated using several risk endpoints as particular measures of human health risk or ecological hazard. A risk endpoint is a specific type of risk estimate (e.g., an individual's excess cancer risk) that is used as the metric for a given risk category. The CCW risk assessment evaluated cancer and noncancer endpoints for humans and noncancer endpoints for ecological receptors. For human risk, the availability of toxicological benchmarks for cancer and noncancer effects determined which endpoints were evaluated for each constituent.

EPA used two risk endpoints to characterize risk for the human receptors and a single risk endpoint, total HQ, to characterize risk for ecological receptors. These endpoints are discussed in **Section 3.9**; in addition, uncertainty related to these endpoints is discussed in **Sections 4.4.2** (exposures to multiple constituents) and **4.4.3.4** (benchmark uncertainties).

From the distribution of risks for each risk endpoint generated by the Monte Carlo analysis, the 50th and 90th percentile risks were selected and compared to a risk range of 1 in 1,000,000 to 1 in 10,000 excess cancers and a hazard quotient greater than 1 for noncarcinogenic effects. A hazard quotient greater than 1 was also used for the ecological risk criterion in the full-scale risk assessment.

3.0 Analysis

The CCW risk analysis evaluated risks from CCWs disposed of in landfills and surface impoundments located onsite at coal-fired utility power plants across the United States based primarily on data collected in 1995 by EPRI (1997).[1] Chemical constituents found in CCW can be released from these WMUs into the surrounding environment by releases through leachate to the subsurface underlying the WMU. Leachate forms in both landfills and surface impoundments, migrates from the WMU through soil to groundwater, and is transported in groundwater to drinking water wells (groundwater-to-drinking-water pathway) and into surface waterbodies near the WMU (groundwater-to-surface-water pathway).

To select the constituents for full-scale modeling, the screening analysis compared very conservative estimates of exposure concentrations (e.g., leachate concentrations) to health-based concentration benchmarks to quickly, simply, and safely identify constituents with risks that clearly do not exceed the risk criteria so that these could be eliminated from further analysis. For example, leachate concentrations were compared directly to drinking water standards, which is equivalent to assuming that human receptors are drinking leachate.

For the full-scale analysis, EPA used computer-based models and sets of equations to estimate the risk to human health and the environment from current CCW disposal practices.[2] These models included

- **Source** models that simulate the release of CCW constituents in leachate from landfills and surface impoundments[3]
- **Fate and transport** models that estimate contaminant concentrations in environmental media such as groundwater and surface water
- **Exposure** models that estimate daily contaminant doses for humans and ecological receptors exposed to CCW constituents in environmental media that were not screened out
- **Risk** models that calculate risks to humans and ecological receptors.

This section describes the data, models, and equations used for CCW constituent screening, as well as those used to calculate exposure point concentrations and risk in the full-

[1] The selection and characterization of these CCW WMUs are described in more detail in Appendix B.

[2] As discussed in **Section 2**, the 1995 EPRI survey data was assumed to represent current CCW management practices. However, new data from a more recent DOE/EPA survey suggest that liners may be more prevalent in new and expanded units built since 1994. **Section 4** discusses implications of this uncertainty on the risk assessment results.

[3] EPA used source-term models integrated into EPACMTP to estimate environmental releases of constituents in leachate from landfills and surface impoundments.

scale analysis. **Section 3.1** describes the health benchmarks used to develop human and ecological risk estimates for screening and full-scale analysis. **Section 3.2** describes the screening analysis, along with how the screening results were used to select constituents for the full-scale analysis. **Section 3.3** provides the overall structure for the full-scale analysis, including the spatial and temporal framework and the probabilistic (Monte Carlo) framework for the model runs. **Sections 3.4** and **3.5** describe the landfill and surface impoundment source models used to predict environmental releases of constituents from CCW. **Sections 3.6** and **3.7** describe the fate and transport modeling used to predict contaminant concentrations in groundwater and surface water. **Section 3.8** describes the human exposure calculations and **Section 3.9** describes how risks were calculated for human and ecological receptors.

Supporting detail can be found in the following appendices:

- **Appendix A, CCW Constituent Data**, provides the CCW constituent concentrations used and describes how they were collected and processed for both the screening and full-scale analyses
- **Appendix B, Waste Management Unit Data**, describes the location and characteristics of each landfill and surface impoundment modeled and describes how the source model input parameter values were collected for the full-scale analysis
- **Appendix C, Site Data**, describes how environmental data around each CCW waste disposal site were collected to provide inputs for the groundwater and surface water modeling
- **Appendix D, MINTEQA2 Nonlinear Sorption Isotherms**, describes the development and application of the CCW-specific MINTEQ metal sorption isotherms used to model fate and transport in soils and groundwater
- **Appendix E, Surface Water, Fish Concentration, and Contaminant Intake Equations**, documents the algorithms used to calculate surface water concentrations, fish concentrations, and drinking water and fish intake rates
- **Appendix F, Human Exposure Factors**, documents the human exposure parameters and equations used for calculating the environmental exposure from CCW disposal
- **Appendix G, Human Health Benchmarks**, describes how the human toxicity benchmarks were selected and developed for CCW constituents
- **Appendix H, Ecological Benchmarks**, describes how the ecological toxicity benchmarks were selected and developed for CCW constituents
- **Appendix I, Calculation of HBNs,** describes how health-based numbers were calculated for the screening analysis
- **Appendix J, Chemical-Specific Inputs Used in the Screening Analysis,** describes additional chemical-specific data used in the screening analysis

- **Appendix K, Screening Analysis Results,** provides the results of the screening analysis for human and ecological receptors.
- **Appendix L, Time of Travel to Receptor Well,** provides figures showing, for selected CCW constituents, cumulative percentiles of the time it took for the peak concentration to reach a receptor well for each source type.

3.1 Toxicity Assessment

The assessment of human risks from disposal of a waste stream like CCW begins by assessing, for constituents in the waste, the ability of each chemical to cause an adverse human health effect, which depends on the toxicity of the chemical, the chemical's route of exposure to an individual (ingestion, inhalation, or direct contact), the duration of exposure, and the dose received (the amount that a human ingests or inhales). Similar principles apply to ecological receptors, although exposure duration is much shorter than for human receptors because humans generally live longer than ecological receptors. For a risk assessment, the toxicity of a constituent is defined by a human health or ecological benchmark for each route of exposure. A benchmark is a quantitative value used to predict a chemical's possible toxicity and ability to induce an adverse effect at certain levels of exposure. Because different chemicals cause different health effects at different doses, benchmarks are chemical-specific.

Appropriate human health and ecological benchmarks for the constituents of potential concern in CCW wastes were collected for use in the screening assessment and in the full-scale risk assessment. Although these assessments were conducted in 2002 and 2003, the benchmarks and risks presented in this 2009 report were updated to reflect current toxicity data.[4] The data sources and collection methodology for these benchmarks are described briefly in **Sections 3.1.1** (human health benchmarks) and **3.1.2** (ecological benchmarks), and in more detail in **Appendix G** (human health benchmarks) and **Appendix H** (ecological benchmarks).

3.1.1 Human Health Benchmarks

Human health benchmarks for chronic oral exposures were needed for the full-scale analysis. These health benchmarks were derived from toxicity data based on animal studies or human epidemiological studies. Each benchmark represents a dose-response estimate that relates the likelihood and severity of adverse health effects to exposure and dose. This section presents the noncancer and cancer benchmarks used to evaluate human health effects that may result from exposure to the constituents modeled.

Chronic human health benchmarks were used to evaluate potential noncancer and cancer risks. These include reference doses (RfDs) to evaluate noncancer risk from oral exposures and oral cancer slope factors (CSFs) to evaluate cancer risk from oral exposures. The benchmarks are chemical-specific and do not vary between age groups.

[4] Because the risk calculations are linear and occur at the end of the analysis, all screening and full-scale results can be simply scaled to accommodate any changes in human health and ecological benchmarks.

- The **RfD** is an estimate (with uncertainty spanning perhaps an order of magnitude) of a daily exposure to the human population (including sensitive subgroups) that is likely to be without appreciable risk of deleterious noncancer effects during a lifetime. The RfD provides a reference point to gauge the potential effects (U.S. EPA, 2002c). At exposures increasingly greater than the RfD, the potential for adverse health effects may increase, although this potential cannot be quantified. Lifetime exposure above the RfD does not imply that an adverse health effect would necessarily occur.

- The **CSF** is an upper-bound estimate (approximating a 95 percent confidence limit) of the increased human cancer risk from a lifetime exposure to an agent. Because this is an upper-bound estimate, true risk is likely lower. This estimate is usually expressed in units of proportion (of a population) affected per milligram of agent per kilogram body weight per day (mg/kg-d). Unlike RfDs, CSFs do not represent "safe" exposure levels; rather, they relate levels of exposure with a probability of effect or risk.

Human health benchmarks are available from several sources. Health benchmarks developed by EPA were used whenever they were available. Sources of human health benchmarks were used in the following order of preference:

- Integrated Risk Information System (IRIS) (U.S. EPA, 2002c)
- Superfund Technical Support Center Provisional Benchmarks
- Health Effects Assessment Summary Tables (HEAST) (U.S. EPA, 1997f)
- Various other EPA health benchmark sources
- ATSDR minimal risk levels (MRLs) (ATSDR, 2002).

These sources and the selection hierarchy are described in more detail in **Appendix G**.

The chronic human health benchmarks used in the screening and full-scale analysis are summarized in **Table 3-1**. For most constituents, human health benchmarks were available from IRIS. Benchmarks for a few constituents were obtained from ATSDR. For chemicals for which purely health-based benchmarks were not available (lead), a drinking water action level was used (U.S. EPA, 2002d).

Table 3-1. Human Health Benchmarks Used in the CCW Risk Assessment

Constituent	Type of Benchmark[a]	Value	Units	Source[b]
Cancer Benchmark				
Arsenic	CSF	1.5E+00	$(mg/kg\text{-}d)^{-1}$	IRIS
Noncancer Benchmarks				
Aluminum	RfD	1.0E+00	mg/kg-d	PPRTV
Antimony	RfD	4.0E-04	mg/kg-d	IRIS
Arsenic	RfD	3.0E-04	mg/kg-d	IRIS
Barium	RfD	2.0E-01	mg/kg-d	IRIS
Beryllium	RfD	2.0E-03	mg/kg-d	IRIS

(continued)

Human Health Benchmarks Used in the CCW Risk Assessment (continued)

Constituent	Type of Benchmark[a]	Value	Units	Source[b]
Boron	RfD	2.0E-01	mg/kg-d	IRIS
Cadmium	RfD (water)[c]	5.0E-04	mg/kg-d	IRIS
	RfD (food)[d]	1.0E-03	mg/kg-d	IRIS
Chromium III	RfD	1.5E-00	mg/kg-d	IRIS
Chromium VI	RfD	3.0E-03	mg/kg-d	IRIS
Cobalt	RfD	3.0E-04	mg/kg-d	PPRTV
Copper	RfD	1.0E-02	mg/kg-d	ATSDR
Cyanide	RfD	2.0E-02	mg/kg-d	IRIS
Fluoride	RfD	6.0E-02	mg/kg-d	IRIS
Lead	MCL	1.5E-02	mg/L	DWAL
Manganese	RfD (food)	1.4E-01	mg/kg-d	IRIS
	RfD (water, soil)	4.7E-02	mg/kg-d	IRIS
Mercury (divalent)	RfD (food, water, soil)	3.0E-04	mg/kg-d	HEAST
	RfD (fish)	1.0E-04	mg/kg-d	IRIS
Molybdenum	RfD	5.0E-03	mg/kg-d	IRIS
Nickel	RfD	2.0E-02	mg/kg-d	IRIS
Nitrate	MCL	1.0E+01	mg/L	DWAL
	RfD	1.6E+00	mg/kg-d	IRIS
Nitrite	RfD	1.0E-01	mg/kg-d	IRIS
Selenium	RfD	5.0E-03	mg/kg-d	IRIS
Silver	RfD	5.0E-03	mg/kg-d	IRIS
Strontium	RfD	6.0E-01	mg/kg-d	IRIS
Thallium	RfD	8.0E-05	mg/kg-d	IRIS
Vanadium	RfD	7.0E-03	mg/kg-d	HEAST
Zinc	RfD	3.0E-01	mg/kg-d	IRIS

[a] MCL = maximum concentration limit
[b] References:
ATSDR: Minimal Risk Levels, ATSDR (2009)
DWAL: Drinking Water Action Level, U.S. EPA (2002d)
HEAST: U.S. EPA (1997f)
IRIS: U.S. EPA (2009a)
PPRTV: Provisional peer-reviewed toxicity value (U.S. EPA, 2006a, 2006b, 2008a)
[c] Used for drinking water ingestion.
[d] Used for fish ingestion.

Cadmium has two RfDs, one for exposures via water and one for exposures via food. The RfD for water was used for drinking water ingestion and the RfD for food was used for fish consumption.

3.1.2 Ecological Benchmarks

The ecological risk assessment addressed two routes of exposure for ecological receptors, direct contact with contaminated media and ingestion of contaminated food items. For each constituent for which ecological effect data were available, HQs were calculated using chemical-specific media concentrations assumed to be protective of ecological receptors of concern. To calculate ecological HQs, these media concentrations (also known as chemical stressor concentration limits [CSCLs]) were divided by the estimated media concentrations. The CSCLs are media-specific environmental quality criteria intended to represent a protective threshold value for adverse effects to various ecological receptors in aquatic ecosystems (surface water and sediment). The CSCLs were developed to be protective of the assessment endpoints chosen for this assessment. An HQ greater than 1 indicates that the predicted concentration exceeds the CSCL, and therefore, the potential for adverse ecological effects exists. In this regard, the use of CSCLs to calculate an ecological HQ is analogous to the use of the reference concentration (RfC) for human health where the air concentration is compared to the health-based concentration (the RfC), and an HQ greater than 1 is considered to indicate the potential for adverse health effects.

Table 3-2 shows the receptor types assessed for each exposure route (direct contact and ingestion) in each environmental medium addressed by the full-scale CCW risk assessment.

Table 3-2. Ecological Receptors Assessed by Exposure Route and Medium (Surface Water or Sediment)

Receptor Type	Surface Water (water column)	Surface Water Sediment
Direct Contact Exposure		
Aquatic Community	✔	
Sediment Community		✔
Amphibians	✔	
Aquatic Plants and Algae	✔	
Terrestrial Plants		
Ingestion Exposure		
Mammals	✔	
Birds	✔	

Ecological receptors that live in close contact with contaminated media are considered to be potentially at risk. For the screening and full-scale analysis, these receptors are exposed through direct contact with contaminants in surface water and sediment. The benchmarks for receptor communities (aquatic or sediment communities) are not truly *community-level* concentration limits in that they do not consider predator-prey interactions. Rather, they are based on the theory that protection of 95 percent of the species in the community will provide a sufficient level of protection for the community (see, for example, Stephan et al., 1985, for additional detail). **Appendix H** summarizes the benchmark derivation methods for each receptor assessed for the direct contact route of exposure.

For surface water and sediments, the ingestion route of exposure addresses the exposure of terrestrial mammals and birds through ingestion of aquatic plants and prey. Thus, the benchmarks for ingestion exposure represent media concentrations that, based on certain assumptions about receptor diet and foraging behavior, are expected to be protective of populations of mammals and birds feeding and foraging in contaminated areas.

For birds and mammals, the derivation of ingestion benchmarks required the selection of appropriate ecotoxicological data based on a hierarchy of sources. The assessment endpoint chosen for birds and mammals was population viability and therefore, the ingestion benchmarks were based on study data for physiological effects that are relevant to populations. These data included measures of reproductive fitness, developmental success, survival, and other toxicological effects that could have an impact on the population rather than just the health of an individual animal. Choosing these measures of effect provided the basis to evaluate the potential for adverse effects at the population level by inference; this analysis did not evaluate the effects on population dynamics in the sense that a reduction in the population was predicted over time in response to exposure to constituents released from CCW. Population-level modeling was beyond the scope of this risk assessment.

Once an appropriate ingestion exposure study was identified, a benchmark was calculated. **Appendix H** describes the basic technical approach used to convert avian or mammalian benchmarks (in daily doses) to the CSCLs (in units of concentration) used to assess ecological risks for contaminated surface water and sediment. The methods reflect exposure through the ingestion of contaminated plants, prey, and various media, and include parameters on accumulation (e.g., BCFs), uptake (e.g., consumption rates), and dietary preferences.

Where multiple ecological benchmarks were available for a pathway of interest, the benchmark that produced the lowest (most sensitive) CSCL for each chemical in each medium was used. For example, several types of receptors (the aquatic community, amphibians, aquatic plants, mammals, birds) can be exposed to contaminants in surface water. The surface water criterion for a given constituent represents the lowest CSCL for these receptors, and thus gives the highest (most protective) HQ. The CSCLs used to assess ecological endpoints in the full-scale analysis and the associated receptor are summarized in **Table 3-3**. Additional details on the CCW ecological benchmarks and CSCLs and their development can be found in **Appendix H** and in U.S. EPA (1998a).

Table 3-3. Ecological Risk Criteria Used for Surface Water and Sediment

Constituent	Medium[a]	Exposure Route	CSCL	Units	Receptor
Aluminum	Surface Water	Direct contact	0.09	mg/L	Aquatic biota
Arsenic total	Sediment	Ingestion	0.51	mg/kg	Spotted sandpiper
Arsenic III	Surface Water	Direct contact	0.15	mg/L	Aquatic biota
Arsenic IV	Surface Water	Direct contact	8.10E-03	mg/L	Aquatic biota
Barium	Sediment	Ingestion	190	mg/kg	Spotted sandpiper
	Surface Water	Direct contact	4.00E-03	mg/L	Aquatic biota
Boron	Surface Water	Direct contact	1.60E-03	mg/L	Aquatic biota

(continued)

Ecological Risk Criteria Used for Surface Water and Sediment (continued)

Constituent	Medium[a]	Exposure Route	CSCL	Units	Receptor
Cadmium	Sediment	Direct contact	0.68	mg/kg	Sediment biota
	Surface Water	Direct contact	2.50E-03	mg/L	Aquatic biota
Cobalt	Surface Water	Direct contact	0.02	mg/L	Aquatic biota
Lead	Sediment	Ingestion	0.22	mg/kg	Spotted sandpiper
	Surface Water[b]	Ingestion	3.00E-04	mg/L	River otter
Selenium total	Surface Water	Direct contact	5.00E-03	mg/L	Aquatic biota
Selenium IV	Surface Water	Direct contact	0.03	mg/L	Aquatic biota
Selenium VI	Surface Water	Direct contact	9.5E-03	mg/L	Aquatic biota

Source: U.S. EPA (1998a)

[a] If a medium (surface water or sediment) is not listed, there were insufficient data to develop a benchmark for it.

[b] Includes ingestion of fish.

3.2 Constituent Screening

The screening risk analysis was designed to select the CCW constituents for full-scale exposure modeling. The groundwater pathway screening evaluated exposure through drinking and surface water contamination[5] from groundwater. The analysis considered risks to both human and ecological receptors. Waste constituents that passed the screen (i.e., were below target risk/hazard criteria) were assumed to pose *de minimis* risks and were not addressed in the full-scale modeling.

3.2.1 Waste Constituent Concentrations

The CCW screening analysis addressed metals and inorganic compounds identified as described in **Section 2.1.1.2**. Waste concentrations were available for most of these constituents from the CCW constituent database described in **Section 2.1.1** and **Appendix A**. The CCW constituent database includes waste analysis data for CCW leachate, surface impoundment and landfill porewater, and whole waste samples, and was used in the screening analysis as follows:

- Analyte concentrations (in mg/L) porewater sampled from surface impoundment sediments represent surface impoundment leachate affecting the groundwater pathways
- To represent landfill leachate, the different types of landfill leachate and porewater data in the CCW constituent database were selected based on a hierarchy developed to best represent CCW landfill waste concentrations at a wide variety of sites and waste disposal conditions.

To allow screening decisions to be made by waste constituent, waste stream, and exposure pathway, CCW data were processed to produce a single concentration per analyte and waste

[5] For the groundwater-to-surface-water pathway, the analysis assumed that human exposure occurs through the consumption of contaminated fish. Ecological exposure occurs through direct contact to contaminated surface water and sediment and consumption of aquatic organisms.

stream (surface impoundment porewater and landfill leachate) for comparison with health-based numbers (HBNs) and CSCLs. Data processing to create these analyte concentrations involved two steps:

- **Calculation of average constituent concentrations by site for landfill leachate, surface impoundment porewater, and total ash concentrations.** Site averaging avoids potential bias toward sites with many analyses per analyte. During site averaging, separate waste disposal scenarios at a site (e.g., non-FBC and FBC ash; FGD sludge and ash) were treated as separate "sites" and averaged independently. Nondetects were averaged at one-half the reported detection limit.[6]

- **Selection of screening concentrations from site-averaged values.** For the screening calculations, the analysis used the 90th percentile of the site-averaged concentrations across all sites for landfill leachate and surface impoundment porewater.

Appendix A describes the CCW constituent database and how the waste constituent concentrations were selected and processed for the screening analysis and full-scale risk assessment.

3.2.2 Media-Specific Exposure Concentrations for Screening

The screening analysis required media concentrations for groundwater, surface water, and sediment to compare with the HBNs and CSCLs. As a simple first screen of risk, the analysis used waste concentrations as protective estimates of offsite groundwater and surface water concentrations.

For groundwater-to-drinking-water exposures, the analysis used the 90th percentile waste porewater[7] and leachate concentrations to represent groundwater contamination from the surface impoundment and landfill, respectively. No dilution or attenuation was assumed between the WMU and the drinking water well because the large size range of CCW units precluded the use of a dilution attenuation factor (DAF)[8] for a nearby well. Similarly, surface water concentrations were assumed to be equivalent to waste leachate and porewater concentrations.

3.2.3 Screening Methodology

The CCW screening approach compared protective health-based concentrations in each medium of concern with estimated offsite media concentrations of CCW constituents described in **Section 3.2.2**. Both human and ecological receptors were addressed. HBNs are media concentrations developed to protect human health, and CSCLs are media concentrations developed to protect ecological receptors. HBNs were calculated based on the target risk criteria

[6] Appendix A contains figures showing how site-averaged 90th percentile concentrations and 90th percentile concentrations taken across all analyses (nonaveraged concentrations) compare with HBNs for surface impoundment porewater, toxicity characteristic leaching procedure (TCLP) leachate, and whole waste concentrations.

[7] Although the 95th percentile was used in 1998, the 90th percentile was used in this analysis as a reasonably conservative value considering the protective screening analysis assumptions and the larger 2002 constituent data set.

[8] A DAF is the waste concentration divided by the media concentration at the point of exposure.

for the screening analysis: an HQ of 1 (for noncarcinogens) or an excess cancer risk level of 10^{-5}. CSCLs were calculated based on an HQ of 1. A full description of the development of the HBNs can be found in **Appendix I**. Development of the CSCLs used for screening based on ecological risks is provided in **Appendix H**.

Screening involved developing these HBNs and CSCLs, as well as developing the waste constituent or media concentrations to be used in the comparison and estimating the risk associated with these concentrations. Pathways and waste streams evaluated in the analysis include those summarized in **Table 3-4**, along with the basic assumptions and methods used to evaluate each pathway in the screening analysis.

Table 3-4. Exposure Pathways Evaluated In CCW Constituent Screening

Exposure Pathway	Methodology
Groundwater-to-drinking-water	Compared drinking water HBNs to landfill leachate and surface impoundment porewater concentrations
Groundwater-to-surface-water (fish consumption; ecological)	Compared surface water HBNs and CSCLs to landfill leachate and surface impoundment porewater concentrations
Direct exposure to surface impoundment CCW (ecological only)	Compared surface water CSCLs to CCW surface impoundment constituent concentrations from the 1998 CCW risk assessment

3.2.3.1 HBN Calculations

HBNs represent media concentrations that are protective of human health from exposure pathways that are relevant to that particular medium. The exposure scenarios assumed for CCW management (see **Section 2.2**) defined the media of concern for the analysis. Human exposure scenarios included the following:

- Drinking of groundwater contaminated by leachate from CCW landfills and surface impoundments
- Consumption of fish by recreational fishers fishing in streams and lakes contaminated by CCW leachate through the groundwater-to-surface-water pathway

The CCW screening analysis used HBNs calculated for groundwater and surface water exposure. The CCW HBNs represent reasonable maximum exposure (RME) scenarios for an offsite receptor:

- Groundwater HBNs are protective for residential drinking water exposure from a domestic well immediately downgradient from a CCW landfill or surface impoundment
- Surface water HBNs are protective for fish caught (and consumed) by a recreational fisher from a river, lake, or stream adjacent to a CCW landfill or surface impoundment.

Key features and assumptions of the HBN calculations included the following:

- HBNs were calculated based on a target cancer risk of 10^{-5} or target HQ of 1

- The analysis considered exposures for three child receptor cohorts and one adult receptor cohort; exposure for these cohorts was assumed to start at ages 3, 8, 15, and 20, respectively
- Chemical properties (bio-uptake and bioaccumulation factors) were collected from best available literature values (see **Appendix J**)
- Human exposure factors (e.g., body weight, exposure duration, exposure frequency, consumption rates) were set at central tendency values.

Appendix I describes the methodology used to develop the CCW HBNs and provides the HBNs used in the screening analysis.

3.2.3.2 CSCL Calculations

The CCW ecological screening analysis paralleled the human health screening analysis and addressed two routes of exposure for ecological receptors: direct contact with contaminated media and ingestion of contaminated food items. Ecological exposure scenarios occurring near CCW landfills or surface impoundments and addressing these exposure routes included the following:

- Direct contact with surface water contaminated by CCW leachate through the groundwater-to-surface-water pathway
- Ingestion of aquatic organisms in streams and lakes contaminated by CCW leachate through the groundwater-to-surface-water pathway.

CSCLs for the contaminated media in each of these exposure scenarios were calculated as described in **Section 3.1.2** and **Appendix H** (the same CSCLs were used for both screening and the full-scale analysis). As with the HBNs, CSCLs were compared directly to concentrations of constituents found in CCW and CCW leachate and porewater, or to protective offsite media concentrations to estimate risk for screening.

3.2.4 Screening Results

The screening analysis conducted in 2002 (U.S. EPA, 2002a) was used in this risk assessment to help narrow the list of constituents to be addressed in the full scale analysis for the groundwater-to-drinking-water and groundwater-to-surface-water pathways. Detailed human and ecological screening results for these pathways are provided in **Appendix K**. The groundwater-to-drinking-water and groundwater-to-surface-water pathways (human fish consumption and ecological risks) did show risks above the screening criteria for several CCW constituents in the screening analysis. **Table 3-5** lists the 21 constituents that had 90th percentile screening analysis groundwater pathway risks greater than a cancer risk of 1 in 100,000 or a noncancer risk with an HQ greater than 1 for human health and 10 for ecological risk.[9]

[9] An HQ of 10 was used for screening ecological risks to account for conservatism of ecological benchmarks and exposure estimates used in the screening analysis (see Section 4.4.3.4).

Table 3-5. Screening Analysis Results: Selection and Prioritization of CCW Constituents for Further Analysis[a]

Constituent	Human Health – Drinking Water		Human Health – Surface Water[b]		Ecological Risk - Surface Water	
	LF HQ (*Cancer Risk*)	SI HQ (*Cancer Risk*)	LF HQ (*Cancer Risk*)	SI HQ (*Cancer Risk*)	LF HQ	SI HQ
Constituents Modeled in Full-scale Assessment						
Carcinogen						
Arsenic[c]	($1.4x10^{-3}$)	($1.8x10^{-2}$)	($2.2x10^{-4}$)	($1.7x10^{-5}$)	49	640
Noncarcinogens						
Boron	4.0	28	-	-	6,600	47,000
Cadmium	3.4	8.9	1.4	3.7	20	52
Lead	16	12	-	-	790	590
Selenium	1.2	2.4	4.7	9.5	35	71
Thallium	21	19	6.3	5.7	-	-
Aluminum	-	-	-	-	120	270
Antimony	22	5.5	-	-	-	-
Barium	-	-	-	-	400	75
Cobalt	-	11	-	-	-	270
Molybdenum	4.2	6.8	-	-	-	-
Nitrate/ Nitrite	- /1.2	60/1.2	-	-	-	-
Constituents Not Modeled in Full-scale Assessment[d]						
Noncarcinogens						
Chromium VI	2.3	4.2	-	-	18	33
Fluoride	1.8	5.2	-	-	-	-
Manganese	1	5.6	-	-	-	-
Vanadium	2.2	2.3	-	-	23	24
Beryllium	-	-	-	-	24	-
Copper	-	-	-	-	16	31
Nickel	-	1.3	-	-	-	14
Silver	-	-	-	-	110	14
Zinc	-	-	-	-	16	-

HQ = screening hazard quotient.
LF = landfill.
SI = surface impoundment.

[a] A dash in a cell indicates that the screening HQ was less than 1 (or 10 for ecological risk), so the risk did not exceed the screening criteria for the indicated pathway.

[b] Fish consumption pathway.

[c] Although arsenic can act as both a carcinogen and a noncarcinogen, the cancer risk exceeds the noncancer risk at any concentration, so the more protective cancer benchmark for human health was used throughout this assessment.

[d] These constituents were addressed using risk attenuation factors developed from full-scale results from modeled constituents (see **Section 4.1.5**).

Note that although mercury was originally addressed in both the 2002 screening and 2003 full-scale analyses, results were removed from the 2007 draft and this version of the risk assessment report because subsequent evaluation found that the very high proportion of mercury nondetects in the CCW constituent database, along with the use of one-half the detection limit for the nondetect measurements, led to the results being driven by the detection limit, rather than the actual (but unknown) levels in CCW leachate and porewater. Therefore, the results were not meaningful in terms of the actual risks mercury in CCW poses to human and ecological health. Similarly, a large number of nondetects (or a very small number of measurements) prevented accurate screening or full-scale analysis for antimony, thallium, and cobalt in surface impoundments. These uncertainties are discussed in **Section 4.4.3.1**.

Full-scale modeling was not conducted for all 21 constituents that had 90th percentile risks above the screening criteria for the groundwater pathways. Instead, those 21 constituents were ranked and divided into two groups to focus the full-scale analysis on the CCW constituents that were likely to pose relatively higher risks to human and ecological receptors. The ranking was based on the magnitude of the HQs and the number of HQs exceeding the screening criteria, and was used to select chemicals for full-scale modeling. Constituents with at least one human health HQ greater than 6 or with ecological HQs greater than 100 for both landfills and surface impoundments were modeled. Arsenic, with cancer risks greater than 1 in 1,000, exceeded the cancer risk criterion by a factor of 100 and was also modeled in the full-scale analysis. Constituents with no human health HQs greater than 6 and only one or no ecological HQs greater than 100 were not modeled, but were addressed in a separate analysis using results from the modeled constituents.

Table 3-5 shows the 21 constituents and which of these constituents exceeded the screening criteria and thus were modeled in the full-scale analysis. As shown, 12 constituents were subjected to the full-scale probabilistic risk assessment described in this document. Another 9 constituents exceeded the screening criteria and were addressed using risk factors developed from comparing the screening and full-scale results for the modeled constituents, as described in **Section 4.1.5** of this document.

3.3 Full-Scale Modeling Approach

This section describes the framework, general assumptions, and constraints for the full-scale probabilistic analysis. **Section 3.3.1** describes the temporal and spatial framework. **Section 3.3.2** describes the probabilistic framework, and **Section 3.3.3** describes how the assessment was implemented within the probabilistic framework.

3.3.1 Spatial and Temporal Framework

The spatial framework for the analysis was determined by the geographic distribution of CCW facilities modeled and by the site layout assumed as the conceptual site model for risk assessment. As described in **Section 2.1.2**, the geographic distribution of landfills and surface impoundments managing wastes onsite at coal-fired utility power plants was determined from the 177 sites in the 1995 EPRI survey of the onsite management of CCW (EPRI, 1997). The assessment assumes that these 177 sites and their locations were representative of the

approximately 300 coal-fired power plants identified by EIA data as having onsite waste management of conventional CCW and CCW codisposed with coal refuse throughout the United States. For FBC wastes, these 177 sites include only 3 FBC landfills. EPA was able to add 4 additional FBC landfill sites to better represent FBC waste management, for an overall total of 181 sites in this analysis.

The conceptual site layouts applied to each of the sites are described and pictured in **Section 2.2.2**. Two site layouts were used to define the relationship between a landfill or surface impoundment and (1) a drinking water well (for human risk via the groundwater-to-drinking-water pathway) and (2) a surface water body (for human and ecological risk via the groundwater-to-surface-water pathway). In each case, the receptor point (well or waterbody) was assumed to lie within the boundaries of the groundwater contaminant plume. The distance from the edge of the WMU to the well or waterbody was varied for each model run based on national distributions, with well distance taken from a national distribution for Subtitle D municipal landfills (U.S. EPA, 1988a) and distance to surface water taken from a set of measured distances for CCW landfills and surface impoundments developed for this assessment. **Appendix C** presents additional details on these distributions.

The temporal framework was mainly defined by the time of travel from the modeled WMU to the well or waterbody, which can be up to one mile away from the edge of the unit, and the exposure duration over which risks were calculated. The subsurface migration of some CCW constituents (e.g., lead) may be very slow; therefore, it may take a long time for the contaminant plume to reach the receptor well or nearest waterbody, and the maximum concentration may not occur until a very long time after the WMU ceases operations. This time delay may be on the order of thousands of years. To avoid excessive model run time while not missing significant risk at the receptor point, the groundwater model was run until the observed groundwater concentration of a contaminant at the receptor point dropped below a minimum concentration (10^{-16} mg/L) or until the model had been run for a time period of 10,000 years. The minimum concentration used for all fate and transport simulations (10^{-16} mg/L) was at least a million times below any risk- or health-based criteria.

For the groundwater-to-drinking-water pathway (human health risk), risks were calculated based on a maximum time-averaged concentration around the peak concentration at each receptor well. The exposure duration (which varies from 1 to 50 years)[10] was applied around the peak drinking well concentration to obtain the maximum time-averaged concentration.

For the groundwater-to-surface-water pathway, the groundwater model produced surface water contaminant loads (based on groundwater concentration and flow) for a stream that penetrates the aquifer. Because the surface water model is a steady-state model, there is no temporal component to it and the receptor is exposed to the same concentration over the entire exposure duration. For human health risk, the loadings from groundwater to surface water were averaged over the exposure duration, bracketing the time of the peak groundwater concentration.

[10] Distributions of exposure duration and other exposure variables were obtained from the *Exposure Factors Handbook* (U.S. EPA, 1997c,d,e) as described in **Section 3.8.2** and **Appendix F**.

The exposure duration for sensitive ecological receptors was generally a year or less; therefore, for ecological risk, a single peak annual average surface water concentration was used.

For all scenarios, if the groundwater model predicted that the maximum groundwater concentration had not yet occurred after 10,000 years, the actual groundwater concentration at 10,000 years was used in the exposure calculations instead of a maximum time-weighted average concentration around the peak.

3.3.2 Probabilistic Approach

The full-scale analysis evaluated risk in a probabilistic manner and was based on a Monte Carlo simulation that produced a distribution of exposures and risks. The general Monte Carlo approach is shown in **Figure 3-1**. The foundation of the Monte Carlo simulation was the source data derived from the EPRI survey. These were combined with data from the national CCW constituent database to conduct a Monte Carlo simulation of 10,000 iterations per waste type/WMU type/constituent combination.

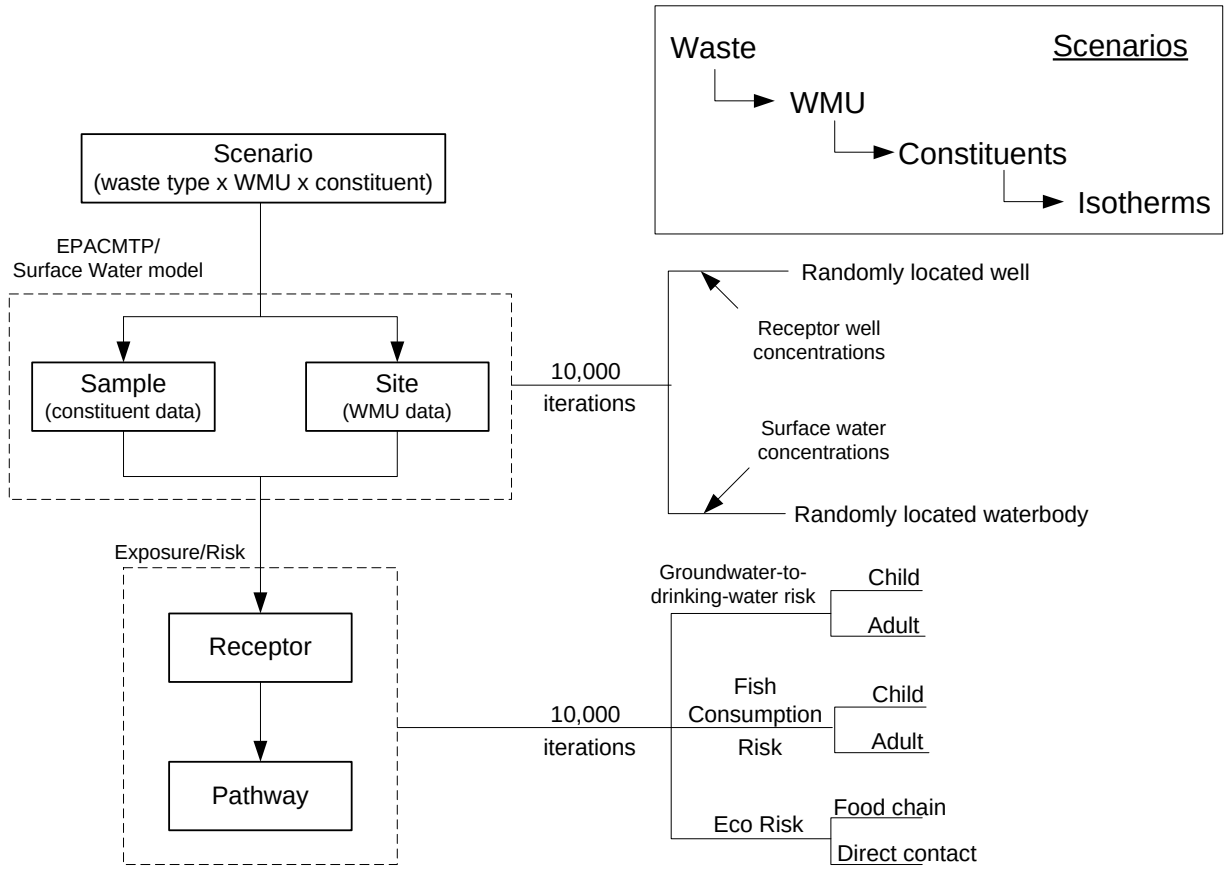


Figure 3-1. Overview of the Monte Carlo approach.

The detailed looping structure for the Monte Carlo analysis is shown in **Figure 3-2**. For each waste type/WMU combination, two separate loops were run. The first loop (shown with dashed lines in Figure 3-2) prepared a set of input files containing 10,000 sets of WMU and site data (as described in **Section 3.3.3**). The second loop (shown with solid lines in Figure 3-2) used

those input files to run 10,000 iterations of the source, fate and transport, exposure, and risk models for each constituent.

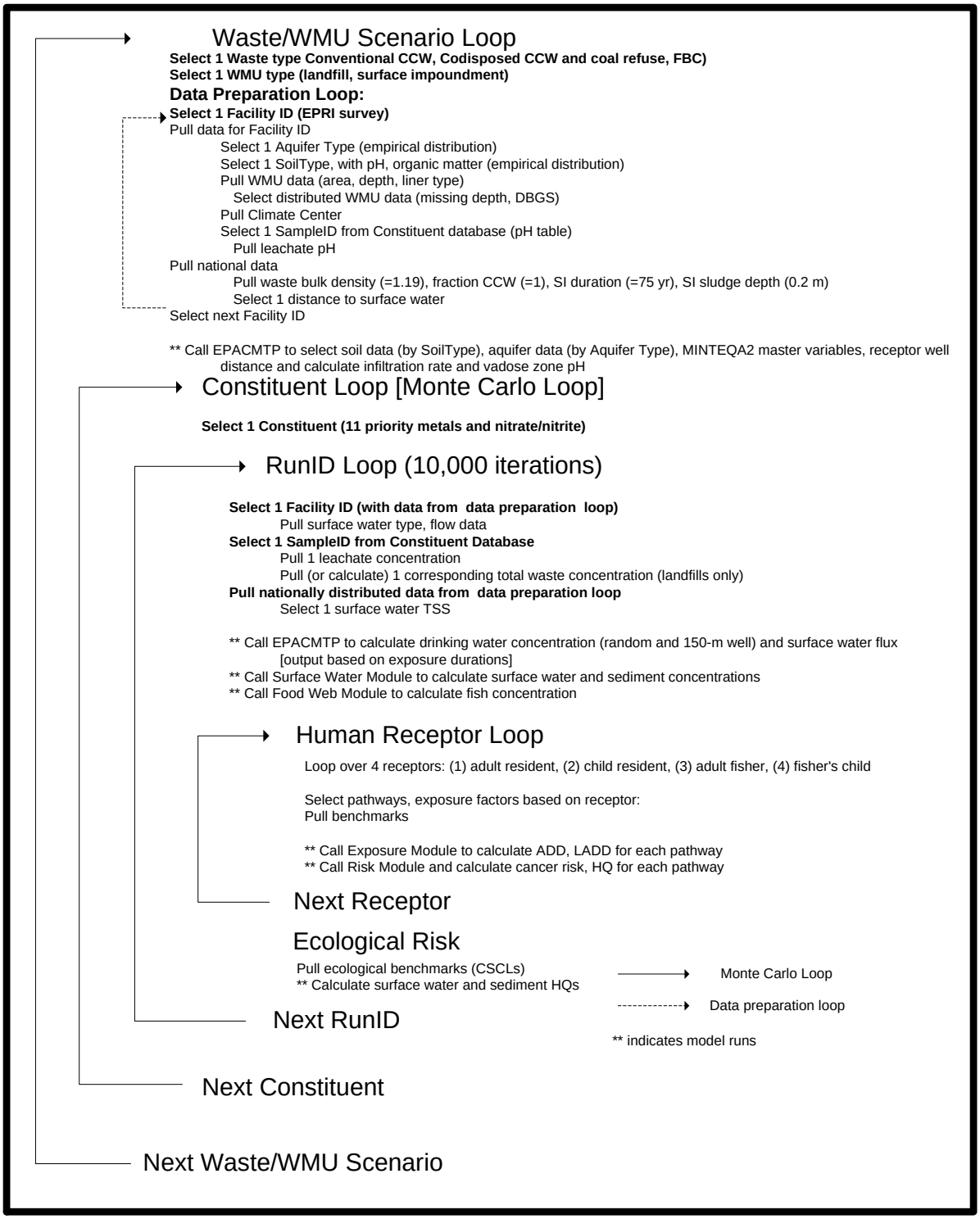


Figure 3-2. Monte Carlo looping structure.

3.3.3 Implementation of Probabilistic Approach

Table 3-6 lists the five waste disposal scenarios addressed in the full-scale analysis. FBC waste landfills were modeled and treated as a separate scenario in the analysis because of the limited number (7) of FBC landfill sites. Each waste disposal scenario modeled in the full-scale assessment included unlined, clay-lined, and composite-lined WMUs. Additional detail on these scenarios can be found in **Section 2.1** and **Appendix A**.

Table 3-6. CCW Waste Management Scenarios Modeled in Full-Scale Assessment

WMU Type	Waste Type
Conventional CCW and CCW Codisposed with Coal Refuse (main analysis)	
Landfill	Conventional CCW (fly ash, bottom ash, boiler slag, FGD sludge)
Landfill	Codisposed CCW and coal refuse
Surface impoundment	Conventional CCW
Surface impoundment	Codisposed CCW and coal refuse
FBC Waste (separate analysis)	
Landfill	FBC waste (fly ash and bottom [bed] ash)

To capture the national variation in waste management practices for the Monte Carlo analysis, an input database was created with approximately 10,000 iterations for each of the waste type/WMU combinations. This input database provided the source data for 10,000 iterations of the source modeling and the fate and transport modeling. **Figure 3-3** provides an overview of the process used to compile these data, which were organized into source data files. As shown in Figure 3-3, seven tasks, some parallel and some sequential, were required to construct these data files, one file for each waste management scenario.

Constructing the source data files for use in the probabilistic analysis involved first developing a 10,000-record data file for each waste type-WMU scenario. This was accomplished by selecting from the EPRI survey data the landfills and surface impoundments that manage each type of waste. Within a scenario, a list of the EPRI plants with that WMU type and waste type was repeated to produce around 10,000 records. For each record, site-based, regional, and national inputs were randomly selected from distributions developed to characterize the regional or national variability in these inputs. Each record in the source data files was identified by a model run identification number (RunID).

The EPRI survey provided most of the WMU data needed, including area, capacity, liner type, and waste type. Additional data were collected to characterize the height and depth below ground surface of typical CCW landfills and surface impoundments (see **Appendix B**).

The environmental setting in which waste disposal occurs was characterized based on the location of the 181 power plants used in the full-scale analysis. These locations were used to characterize climate, soils, aquifers, and surface water bodies at each site as follows (see **Appendix C** for details):

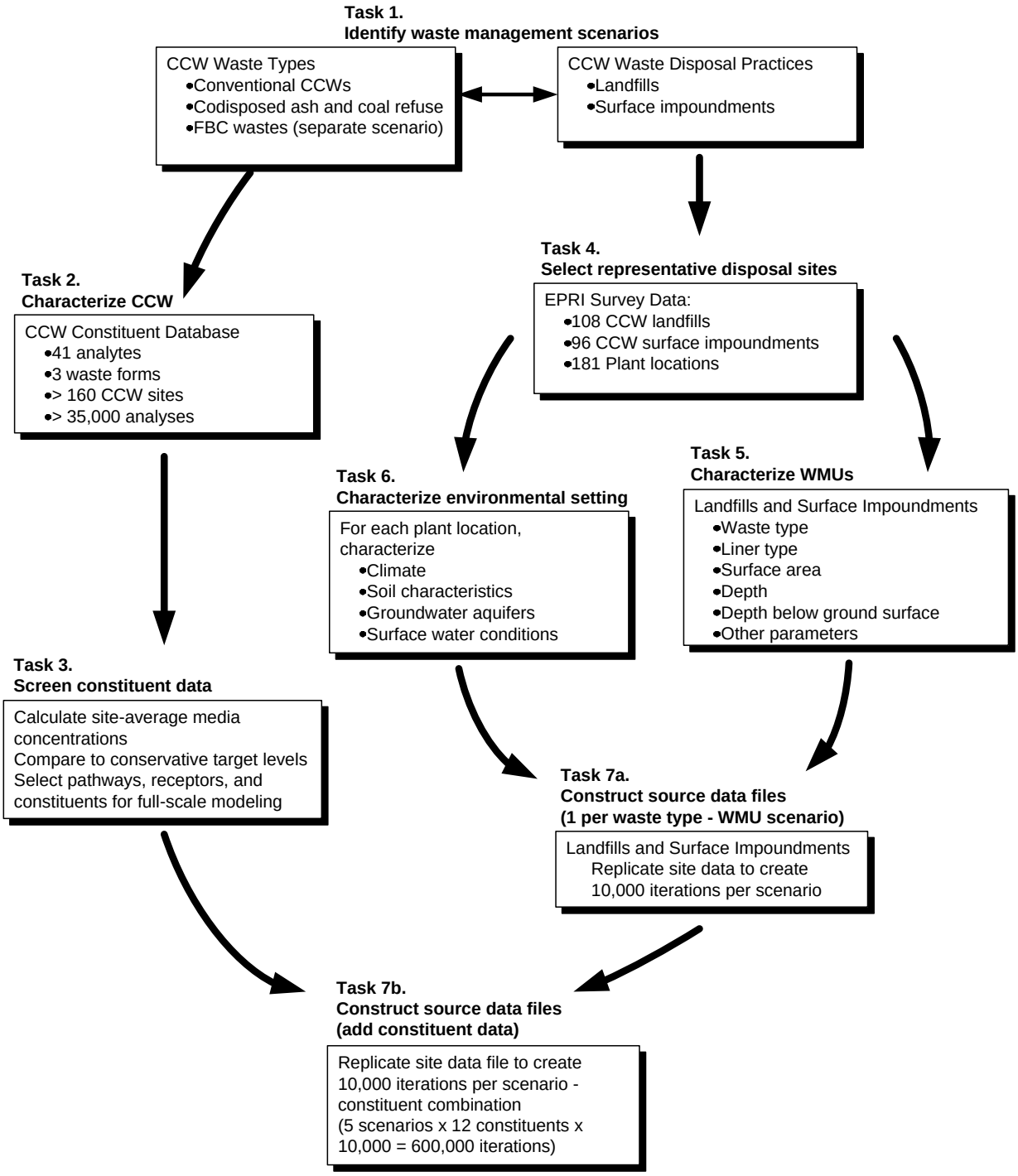


Figure 3-3. Process used to construct the Monte Carlo input database.

- Climatic data, including precipitation and infiltration rates, were collected by assigning each site to a nearby HELP climate center (see **Section 3.4.2.1** for a discussion of the HELP landfill infiltration model).

- Soil and aquifer type were collected within a 5-km radius of each site location to account for locational uncertainty for the WMUs (site location are often facility centroids or front gate locations).

- Surface water type and flows were collected using a geographic information system (GIS) to identify the nearest stream and by matching plants to the Permit Compliance System (PCS) database to get the stream segment for each plant's NPDES discharge point.

These site-based data were supplemented with regional data on surface water quality and with national distributions of receptor distances (i.e., distance to drinking water well and distance to nearest surface waterbody). **Appendix C** describes the site-based approach and data sources used for these site-specific, regional, and national-scale data collection efforts.

The five 10,000-record scenario-specific source data files were then combined with the CCW constituent data for each constituent in the appropriate waste type to develop the final source data files for each scenario. With 12 constituents modeled for most scenarios, this resulted in over 600,000 records in the final input data set.

3.4 Landfill Model

Releases from landfills were modeled using a landfill source-term model contained in EPACMTP. EPA has used EPACMTP and its predecessor models for almost 20 years to conduct groundwater risk assessments in support of regulations for land disposal of hazardous and nonhazardous wastes. In that context, EPACMTP has undergone numerous peer reviews, including multiple reviews by EPA's Science Advisory Board (SAB). Each of these reviews has supported and approved the use of this model for developing national regulations and guidance, including verification that the model and model code are scientifically sound and properly executed. Some of the more important reviews include

- A 1989 review by SAB of the component saturated zone (groundwater) model used in EPACMTP

- A 1993 review by EPA's Office of Research and Development (ORD) of EPACMTP for potential Hazardous Waste Identification Rule applications, which resulted in a number of improvements in the computational modules of EPACMTP

- A 1994 consultation with SAB on the use of EPACMTP for determination of dilution-attenuation factors for EPA's *Soil Screening Guidance*

- A 1994 review by expert modelers Dr. Fred Molz (Auburn University) and Mr. Chris Neville (SS Papadopoulos & Associates), who verified that the mathematical formulation of the model and the code verification testing are scientifically sound

- The peer-reviewed publication of EPACMTP in the *Journal of Contaminant Hydrology* (Kool et al., 1994)

- An in-depth review by SAB related to the use of EPACMTP in the proposed/draft 1995 Hazardous Waste Identification Rule (U.S. EPA, 1995)
- A 1999 peer review by leading modelers of the implementation of EPACMTP in EPA's multimedia, multiple exposure pathway, multiple receptor risk assessment (3MRA) model (U.S. EPA, 1999c)
- A 2003 SAB review of the 3MRA implementation of EPACMTP (SAB, 2004).

An overview and statement of assumptions for the landfill model is presented here, followed by a listing of inputs to the landfill source-term model and a brief discussion of the output generated by the model.

3.4.1 Conceptual Model

The landfill model treats a landfill as a permanent WMU with a rectangular footprint and a uniform depth (see **Figure 3-4**). If only the area is known (which is the case for the CCW landfills), the landfill source-term model assumes a square footprint. The model assumes that the landfill is filled with waste during the unit's operational life and that upon closure of the landfill, the waste is left in place and a final soil cover is installed.

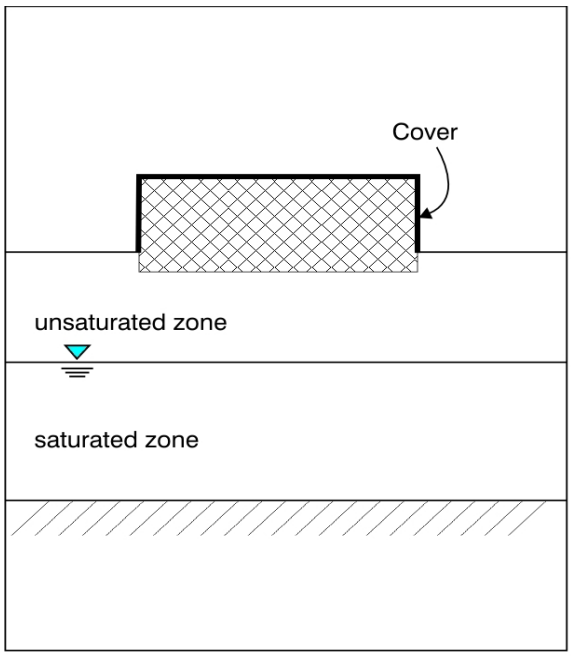


Figure 3-4. Conceptualization of a landfill in the landfill source-term model.

Three liner scenarios were modeled: a no-liner (unlined) scenario, a compacted clay liner, and a composite liner that combines a high-density polyethylene (HDPE) membrane with either geosynthetic or natural clays.

In the unlined scenario, waste is placed directly on local soils, either on grade or excavated to some design depth and without a leachate collection system. After the landfill has been filled to capacity, a 2-foot native soil cover (the minimum required by Subtitle D regulations) is installed and assumed to support vegetation.

In the clay liner scenario, waste is placed directly on a 3-foot compacted clay liner, which is installed on the local soils, either on grade or excavated to some design depth and without a leachate collection system. After the landfill has been filled to capacity, a 3-foot clay cover is installed and covered with 1 foot of loam to support vegetation and drainage. The hydraulic conductivity of both the liner and cover clays is assumed to be $1x10^{-7}$ cm/sec, the typical design specification for compacted clay liners (U.S. EPA, 1988c).

In the composite liner scenario, wastes are placed on a liner system that consists of a 60 mil HDPE membrane with either an underlying geosynthetic clay liner or a 3-foot compacted clay liner. A leachate collection system is also assumed to exist between the waste and the liner system. After the landfill has been filled to capacity, a 3-foot clay cover is assumed to be installed and covered with 1 foot of loam to support vegetation and drainage (U.S. EPA, 2002b).

As described in **Section 3.4.3** (and **Appendix B**), one of these three liner types was assigned to each CCW landfill or surface impoundment modeled based on the liner type data from the 1995 EPRI Survey (EPRI, 1997).

3.4.2 Modeling Approach and Assumptions

The starting point for the landfill source-term model simulation was the time when the landfill is closed (i.e., when the unit is filled with CCW).[11] As described in detail below, the full-scale analysis modeled contaminants leaching from CCW into precipitation infiltrating the landfill, which exits the landfills as leachate. Contaminant loss in leachate was taken into account at closure by subtracting the cumulative amount of contaminant mass loss that occurred during the unit's active life from the amount of contaminant mass present at the time of landfill closure. Loss calculations in the landfill source-term model continued after closure until the contaminant was depleted from the waste mass in the landfill. This is a conservative assumption, as some metal will not leach from the waste mass.

3.4.2.1 Infiltration and Leaching

The average rate at which water percolates through a landfill over time (the long-term infiltration rate) drives the leaching process in the landfill, which results from partitioning of the constituent from the waste into the infiltrating water. The methodology, assumptions, and data

[11] The simple landfill model used in this assessment cannot model a landfill as it is being filled prior to closure. Although leaching does occur during a landfill's operating life, risks from these releases are insignificant when compared to postclosure releases, given the long time it takes metal-bearing wastes to leach and reach peak concentrations in groundwater wells surrounding the landfill. For lined units, the liner system would be functional and governing during the active period of the landfill. For the unlined case, the landfill model assumes that the cap soils are no less permeable than the ambient soils around and under the landfill. So the majority of the cases would not have greater infiltration before closure. For these reasons, EPA does not believe that the additional risks from the preclosure period justify the additional complexity, data, and effort required to model an operating landfill.

used to determine infiltration rates for each CCW liner scenario were consistent with the approach used in EPA's Industrial D guidance, as described in Section 4.3 and Appendix A of the *EPACMTP Parameter/Data Background Document* (U.S. EPA, 2003a) and Section 4.2.2 of the *Industrial Waste Evaluation Model (IWEM) Technical Background Document* (U.S. EPA, 2002b). EPA developed the IWEM model as part of a guide for managing nonhazardous industrial wastes in landfills and surface impoundments (http://www.epa.gov/industrialwaste). To help ensure that it was technically sound, the model (including the liner scenarios and algorithms used in the CCW risk assessment) was developed with a large stakeholder working group, including representatives from industry. The model was also subjected to a peer review in 1999 (64 FR 54889–54890, October 8, 1999, *Peer Reviews Associated with the Guide for Industrial Waste Management*), and the model was updated and improved in response to those comments before its final release in 2003. That update included the addition of a more robust liner leakage database to support the existing algorithms for calculating infiltration rates through composite liner systems.

No-Liner (Unlined) Scenario. For the no-liner scenario, infiltration rates were selected from a database in EPACMTP that contains 306 infiltration rates already calculated using EPA's Hydrologic Evaluation of Landfill Performance (HELP) water balance model (Schroeder, et al., 1994a, b). HELP is a product of an interagency agreement between EPA and the U.S. Army Corps of Engineers Waterways Experiment Station, and was subjected to the Agency's peer and administrative review. All of the infiltration rates were calculated based on the single typical landfill design described in **Section 3.4.1**, with the only variables that changed between HELP simulations being the meteorological data associated with 102 nationwide climate centers and the type of cover soil applied at closure. Three cover soil categories representing coarse-grained soils, medium-grained soils, and fine-grained soils were used. The selection of an infiltration rate from the database depends on the type of cover soil selected for the landfill and the assignment of the landfill to a HELP climate center. The unlined HELP-derived infiltration rates are presented in U.S. EPA (2003a) by climate center. The assignment of HELP climate centers and soil categories to each CCW site modeled is described in **Appendix C**.

Clay Liner Scenario. The clay liner scenario is very similar to the unlined scenario in that previously calculated HELP infiltration rates for a single clay-lined, clay-capped landfill design were used. The scenario was based on a typical engineered compacted clay liner that is 3 feet thick with a design hydraulic conductivity of $1x10^{-7}$ cm/sec. The one difference from the unlined case is that the clay liner and cover control the rate of water percolation through the landfill and thus infiltration rate does not vary with cover soil (i.e., there is one clay liner infiltration rate per climate center). The clay liner HELP-derived infiltration rates are provided in U.S. EPA (2003a).

Composite Liner Scenario. Composite liner infiltration rates were compiled from monthly average leak detection system (LDS) flow rates for industrial landfill cells reported by TetraTech (2001). The liner configurations are consistent with the composite liner design assumptions presented in **Section 3.4.1** and are the same as those assumed for defaults in EPA's Industrial D landfill guidance (U.S. EPA, 2002b). The LDS flow rates were taken from 27 municipal landfill cells and used in the IWEM model (U.S. EPA, 2002b). As shown in **Table 3-7**, these LDS flow rates included 22 operating landfill cells and 5 closed landfill cells

located in eastern United States: 23 in the northeastern region, 1 in the mid-Atlantic region, and 3 in the southeastern region. Each of the landfill cells is underlain by a geomembrane/ geosynthetic clay liner which consists of a high-density polyethylene geomembrane of thickness between 1 and 1.5 mm, overlying a 6-mm composite geosynthetic clay layer consisting of two geotextile outer layers with a uniform core of bentonite clay to form a hydraulic barrier. Each liner system is underlain by an LDS.

Table 3-7. Leak Detection System Flow Rate Data Used to Develop Landfill Composite Liner Infiltration Rates

Cell ID	Status	Flow Rate (m/y)	Location
G228	Operating	2.1E-04	Mid-Atlantic
G232	Operating	4.0E-04	Northeast
G232	Closed	7.3E-05	Northeast
G233	Operating	0	Northeast
G233	Closed	0	Northeast
G234	Operating	7.3E-05	Northeast
G234	Closed	0	Northeast
G235	Operating	1.5E-04	Northeast
G235	Closed	3.7E-05	Northeast
G236	Operating	3.7E-05	Northeast
G236	Closed	0	Northeast
G237	Operating	7.3E-05	Northeast
G238	Operating	0	Northeast
G239	Operating	7.3E-05	Northeast
G240	Operating	0	Northeast
G241	Operating	0	Northeast
G242	Operating	0	Northeast
G243	Operating	0	Northeast
G244	Operating	0	Northeast
G245	Operating	0	Northeast
G246	Operating	0	Northeast
G247	Operating	0	Northeast
G248	Operating	0	Northeast
G249	Operating	7.3E-05	Northeast
G250	Operating	2.2E-04	Southeast
G251	Operating	0	Southeast
G252	Operating	0	Southeast

Source: U.S. EPA (2002a); original data from TetraTech (2001).

As described in U.S. EPA (2002b), only a subset of the TetraTech (2001) flow rates were used to develop the composite liner infiltration rates. LDS flow rates for geomembrane/ compacted clay composite-lined landfill cells were not used in the distribution because compacted clay liners (including composite geomembrane/compacted clay liners) can release water during consolidation and contribute an unknown amount of water to LDS flow, which makes it difficult to determine how much of the LDS flow is due to liner leakage versus clay

consolidation. Also, LDS flow rates from three geomembrane/geosynthetic clay lined-cells were not used. For one cell, postclosure flow rates were very high, and were more than twice as high as those recorded during the cell's operating period. Data were not used for two other cells because of inconsistencies with the data for the 27 landfill cells used to develop composite liner infiltration rates (U.S. EPA, 2002b). The composite liner infiltration rates were specified as an empirically distributed input to the landfill model (see U.S. EPA, 2003a).

3.4.2.2 Source Depletion and Mass Balance

For this assessment**,** the landfill source-term model represented releases from landfills as a finite source where the mass of a constituent in a landfill is finite and depleted over time by leaching. The landfill source-term model was set as a pulse source, where the leachate concentration is constant over a prescribed period of time and then goes to zero when the constituent is depleted from the landfill. A pulse source is appropriate for metals and other constituents whose sorption behavior is nonlinear. Because all but one (nitrate/nitrite) of the constituents addressed in the full-scale analysis were metals, releases from landfills were modeled as pulse sources.

For a pulse source, basic mass balance considerations require leaching from the landfill to stop when all of the constituent mass has leached from the landfill. For the constant concentration pulse source condition, the pulse duration is given by

$$TSOURC = \frac{CWASTE \times DEPTH \times FRACT \times CTDENS}{CZERO \times SINFIL} \tag{3-1}$$

where

TSOURC	=	Pulse duration (yr)
CWASTE	=	Constituent concentration in the waste (mg/kg)
DEPTH	=	Depth of landfill (m)
FRACT	=	Volume fraction of the landfill occupied by the waste (unitless)
CTDENS	=	Waste density (g/cm^3)
CZERO	=	Initial waste leachate concentration (mg/L)
SINFIL	=	Annual areal infiltration rate (m/yr).

The landfill source-term model uses the above relationship to determine the leaching duration. More details regarding the waste concentration and WMU parameters in Equation 3-1 are provided below and in **Appendices A** and **B**.

3.4.3 Landfill Model Input Parameters

Input parameters required by the landfill source-term model are discussed below. Additional details on how data for these inputs were collected for the CCW risk assessment are provided in **Appendix A** for leachate and waste concentrations and **Appendix B** for landfill dimensions and characteristics.

- **Landfill Area.** The model uses landfill area to determine the area over which infiltration rate occurs and, along with landfill depth and waste concentration, to calculate the total

contaminant mass in the landfill. CCW landfill area data were obtained from the EPRI comanagment survey (EPRI, 1997). The landfill was assumed to be square.

- **Landfill Depth.** Landfill depth is one of several parameters used by the landfill source-term model to calculate the contaminant mass in the landfill. For CCW landfills, average waste depth was estimated by dividing landfill capacity by landfill area. CCW landfill capacity data were taken from the EPRI comanagement survey (EPRI, 1997).

- **Depth Below Grade.** The depth of the bottom of the landfill below the surrounding ground surface is used, along with depth to groundwater, to determine the thickness of the unsaturated zone. For CCW landfills, depth below grade was determined from a national distribution based on available measurements from a number of CCW landfills (see **Appendix B**).

- **Waste Fraction.** The landfills were assumed to be CCW monofills, which corresponds to a waste fraction of 1.0.

- **Waste Density.** The average waste bulk density, as disposed, is used to convert waste volume to waste mass. The waste bulk density for all CCW waste types was assumed to be 1.19 g/cm^3 (U.S. EPA, 1998b).

- **Leachate Concentration.** The concentration of waste constituents in leachate was assumed to be constant until all of the contaminant mass initially present in the landfill has leached out, after which the leachate concentration was assumed to be zero. The constant value used for leachate concentration is from EPA's CCW Constituent Database, described in **Appendix A**.

- **Waste Concentration.** In the finite-source scenario modeled, the total waste concentration is used, along with the waste bulk density and landfill area and depth, to determine the total amount of a constituent available for leaching. Measured total CCW concentrations were paired with leachate concentrations, as described in **Appendix A** and provided in **Attachment A-2**.

- **Liner Type.** The type of liner is used to determine the infiltration/leaching scenario used to calculate leachate flux from the landfill. **Table 3-8** shows the crosswalk used to assign one of the three liner scenarios to each facility based on the liner data in the 1995 EPRI survey (EPRI, 1997). **Attachment B-2** to **Appendix B** provides these assignments, along with the original EPRI liner type, for each CCW landfill facility modeled. One uncertainty in these liner assumptions is how representative the EPRI survey data are of current conditions at coal combustion facilities.

Table 3-8. Crosswalk Between EPRI and CCW Source Model Liner Types

EPRI Liner Type	Model Liner Code	Description
Compacted ash	0	no liner
Compacted clay	1	clay

(continued)

Crosswalk Between EPRI and CCW Source Model Liner Types (continued)

EPRI Liner Type	Model Liner Code	Description
Composite clay/membrane	2	composite
Double	2	composite
Geosynthetic membrane	2	composite
None/natural soils	0	no liner

3.4.4 Model Outputs

For each year in the simulation, the landfill source-term model uses the average annual leachate concentration and infiltration rate to calculate a constituent flux through the bottom of the landfill. This time series was used as an input for the EPACMTP unsaturated zone model.

3.5 Surface Impoundment Model

Releases from surface impoundments were modeled using a surface impoundment source-term model contained in EPACMTP. An overview and statement of assumptions for the surface impoundment model are presented here, followed by a listing of inputs to the surface impoundment source-term model and a brief discussion of the output generated by the model. The primary differences between the treatment of landfills and surface impoundments are (1) the integration of the surface impoundment source term into the unsaturated flow solution, and (2) clean closure of the impoundment after the operating period is over.

3.5.1 Conceptual Model

The surface impoundment model treats a surface impoundment as a temporary WMU with a prescribed operational life. Unlike the landfill model, clean closure is assumed; that is, at the end of the unit's operational life, the model assumes that all wastes are removed and there is no further release of waste constituents to groundwater. Although this simplifying assumption limits the length of potential exposure, and is not consistent with the practice to close CCW surface impoundments with these wastes in place, the peak annual leachate concentrations on which the CCW risk results are based are not likely to be affected, because they are highest when the surface impoundment is in operation due to the higher hydraulic head in an operating impoundment, which drives leachate into the underlying soil with greater force than infiltration after the impoundment is covered and closed. This higher head results in a greater flux of contaminants to groundwater during the active life of the surface impoundment, especially in unlined units. These assumptions are discussed further in **Section 3.5.3.**

Following the unit's closure, the surface impoundment model assumes that the contaminated liquid and sediment in the surface impoundment are replaced by uncontaminated liquid and sediment with otherwise identical configurations and properties. The contaminants that have migrated to the unsaturated zone during operation continue to migrate towards the water table with the same infiltration rate as during operation. By continuing infiltration after the wastes are removed, the infiltration through the surface impoundment unit can be modeled as a

single steady-state flow regime until concentrations in groundwater are no longer affected by constituents released from the surface impoundment during its operation.

The EPACMTP surface impoundment model assumes a square footprint and a constant ponding depth during the impoundment's operational life (**Figure 3-5**). For an unlined impoundment, the model assumes that while the impoundment is in operation, a consolidated layer of sediment accumulates at the bottom of the impoundment. The leakage (infiltration) rate through the unlined impoundment is a function of the ponding depth in the impoundment and the thickness and effective permeability of the consolidated sediment layer at the bottom of the impoundment. The rate of leakage is constrained to ensure that there is not a physically unrealistic high rate of leakage, which would cause groundwater mounding beneath the unit to rise above the ground surface. Underlying the assumption of a constant ponding depth, the surface impoundment source-term model assumes that wastewater in the impoundment is continually replenished while the impoundment is in operation. It also assumes, from the beginning of the unit's operation, that the sediment is always in equilibrium with the wastewater (i.e., the presence of sediment does not alter the concentration of leachate). Accordingly, the surface impoundment source-term model also assumes that the leachate concentration is constant during the impoundment operational life and equal to the concentration in the porewater in the sediments at the bottom of the impoundment.

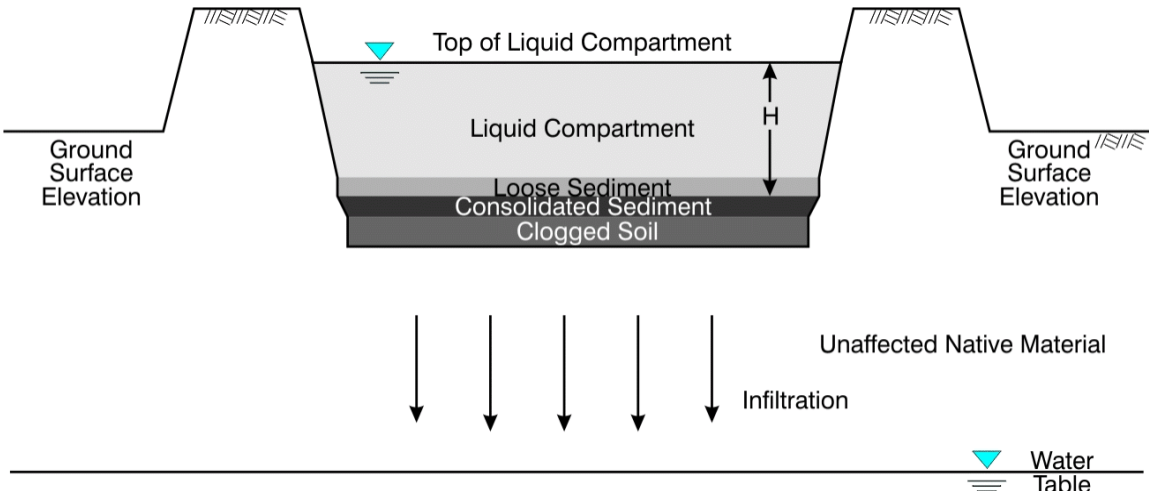


Figure 3-5. Schematic cross-section view of surface impoundment.

Three liner scenarios were modeled: a no-liner (unlined) scenario, a compacted clay liner, and a composite liner.

In the unlined scenario, wastewater is placed directly on local soils and the depth of water is constant over the entire life of the impoundment, pre- and post-closure. As described above, sediments accumulate and consolidate at the bottom of the impoundment and migrate into the underlying native soils, where they clog pore spaces and provide some barrier to flow. The surface impoundment model assumes that the thickness of the consolidated sediments is equal to one-half of the total sediment thickness, which is an input to the model. The sediment thickness was assumed to be 0.2 m for all simulations. The model also assumes that the thickness of the

clogged region of native soils is always 0.5 m and has a hydraulic conductivity 10 percent of that of the native soil underlying the impoundment.

In the clay liner scenario, wastewater is placed on a compacted clay liner, which is installed on the local soils. The assumptions for an unlined impoundment also apply to the compacted clay liner scenario, except that a compacted clay liner filters out the sediments that clog the native soils in the unlined case, so the effect of clogging the native materials is not included in the calculation of the infiltration rate. The thickness of the compacted clay liner was assumed to be 3 feet and the hydraulic conductivity was assumed to be $1x10^{-7}$ cm/sec (U.S. EPA, 1988c).

In the composite liner scenario, wastewater is placed on a synthetic membrane with an underlying geosynthetic or natural compacted clay liner with a hydraulic conductivity of $1x10^{-7}$ cm/sec. The membrane liner was assumed to have a number of pinhole leaks of uniform size (6 mm^2). The distribution of leak densities (expressed as number of leaks per hectare) was compiled from 26 leak density values reported in TetraTech (2001), the best available data on liner leaks. These leak densities are based on liners installed with formal construction quality assurance programs. The 26 sites with leak density data are mostly located outside the United States: 3 in Canada, 7 in France, 14 in the United Kingdom, and 2 in unknown locations; EPA assumed that these are representative of U.S. conditions. The WMUs at these sites (8 landfills, 4 surface impoundments, and 14 of unknown type) are underlain by a layer of geomembrane with a thickness varying from 1.14 mm to 3 mm. The majority of the geomembranes (23 of 26) are made from HDPE, and the remaining 3 are made from prefabricated bituminous geomembrane or polypropylene. One of the sites has a layer of compacted clay liner beneath the geomembrane; however, for 25 of the 26 sites, material types below the geomembrane layer are not reported. The empirical distribution used in the analysis can be found in IWEM (U.S. EPA, 2002b), along with a table showing details about the 26 liners used to develop the distribution.

3.5.2 Modeling Approach and Assumptions

Figure 3-5 illustrates a compartmentalized surface impoundment with stratified sediment. Shown in the figure are the liquid compartment, the sediment compartment (with loose and consolidated sediments), and the unsaturated zone (with clogged and unaffected native materials). The model assumes that all sediment layer thicknesses remain unchanged throughout the life of the unit.

The EPACMTP surface impoundment model uses the unsaturated zone flow model to calculate the infiltration rate out of the bottom of the impoundment. This model is designed to simulate steady-state downward flow through an unsaturated (vadose) zone consisting of one or more soil layers. Steady-state means that the rate of flow does not change with time. In the case of flow out of an unlined surface impoundment, the model simulates flow through a system consisting of three layers: a consolidated sediment layer, a clogged soil layer, and a native soil layer.

The native unsaturated soil extends downward to the water table. The steady-state infiltration rate out of the surface impoundment is driven by the head gradient between the water ponded in the impoundment and the head at the water table. The pressure head at the top of the

consolidated sediment layer is equal to the water depth in the impoundment plus the thickness of the unconsolidated sediment.

The *EPACMTP Technical Background Document* (U.S. EPA, 2003c) describes the algorithms used in this model to calculate the infiltration rate from surface impoundment units, and discusses in detail the maximum allowable infiltration rate based on the groundwater mounding condition. This information is summarized here.

The EPACMTP surface impoundment source-term model calculates infiltration through the accumulated sediment at the bottom of an impoundment, accounting for clogging of the native soil materials underlying the impoundment, liner conditions, and mounding due to infiltration. The modeled infiltration is governed by the depth of liquid in the impoundment and the following limiting factors:

- **Effective hydraulic conductivity and thickness of the consolidated sediment layer.** As sediment accumulates at the base of the impoundment, the weight of the liquid and upper sediments tends to compress (or consolidate) the lower sediments. The consolidation process reduces the hydraulic conductivity of the sediment layer, and the layer of consolidated sediment will act as a restricting layer for flow out of the impoundment. By contrast, the layer of loose, unconsolidated sediment that overlies the consolidated sediment layer is assumed not to restrict the flow rate out of the unit, so it is not explicitly considered in the surface impoundment flow model.

- **Effective hydraulic conductivity of the clogged native material.** As liquids infiltrate soil underlying the impoundment, suspended particulate matter accumulates in the soil pore spaces, reducing hydraulic conductivity and lowering infiltration rates.

- **Effective hydraulic conductivity and thickness of a clay liner.** When the surface impoundment is underlain by a compacted clay liner, the rate of infiltration is also determined by simulating flow through a three-layer system, substituting the characteristics of the clay liner for those of the clogged soil layer.

- **Leak rate of a composite liner.** For cases where the surface impoundment is underlain by a composite liner (a geomembrane underlain by a low permeability liner such as a compacted clay liner or a geosynthetic clay liner), the surface impoundment source-term model uses a modified equation of Bonaparte et al. (1989) to calculate the infiltration rate. The equation uses, among other inputs, the head generated by the water and unconsolidated sediments in the unit, a leak density selected from an empirical distribution derived from a TetraTech (2001) study of liner leakage, a uniform leak size of 6 mm^2, and an assumed hydraulic conductivity of $1x10^{-7}$ cm/sec for the 3 feet of underlying compacted clay material.

- **Limitations on maximum infiltration rate from mounding.** If the calculated infiltration rate exceeds the rate at which the saturated zone can transport the groundwater, the groundwater level will rise into the unsaturated zone. The model accounts for groundwater mounding when calculating the infiltration rate from the

surface impoundment unit and, if necessary, constrains the value to ensure that the groundwater mound does not rise to the bottom of the surface impoundment unit.

3.5.3 Surface Impoundment Model Input Parameters

Input parameters required by the surface impoundment source-term model are discussed below. Additional details on how data for these inputs were collected for the CCW risk assessment are provided in **Appendix A** for waste concentrations and **Appendix B** for surface impoundment dimensions and characteristics.

- **Surface Impoundment Area.** The model uses surface impoundment area to determine the area over which infiltration occurs. CCW surface impoundment area data were obtained from the EPRI comanagement survey (EPRI, 1997). The impoundment was assumed to be square.

- **Areal Infiltration Rate.** The surface impoundment leachate infiltration rate (or flux) is computed internally by the surface impoundment source-term model, as described in **Section 3.5.2**.

- **Depth Below Grade.** The depth of the bottom of the impoundment below the surrounding ground surface is used, along with depth to groundwater, to determine the thickness of the unsaturated zone beneath the impoundment. For CCW impoundments, depth below grade was sampled from an empirical distribution based on available measurements from a number of CCW surface impoundments (see **Appendix B**).

- **Operating Depth.** The operating (or ponding) depth is the long-term average depth of wastewater and sediment in the impoundment, measured from the base of the impoundment. For CCW surface impoundments, depth was estimated by dividing impoundment capacity by impoundment area. CCW impoundment capacity data were taken from the EPRI comanagement survey (EPRI, 1997).

- **Total Thickness of Sediment.** By default, EPACMTP models unlined surface impoundments with a layer of “sludge” or sediment above the base of the unit. The sediment layer is divided into two sublayers: an upper, loose sediment sublayer and a lower, consolidated sediment sublayer. The consolidated sediment has a relatively low hydraulic conductivity and acts to impede flow. The calculated infiltration rate is inversely related to the thickness of the consolidated sediment sublayer. A thinner consolidated sediment layer will result in a higher infiltration rate and a greater rate of constituent loss from the impoundment. The surface impoundment source-term model uses the total sediment thickness as an input parameter and assumes that it consists of equal thicknesses of loose and consolidated material. Because data were not available on CCW sediment layer thicknesses, the CCW risk assessment used the Tier 1 IWEM model assumption: a total (unconsolidated plus consolidated) sediment layer thickness of 0.2 meters (U.S. EPA, 2002b). It is not known how representative this assumption is with respect to unlined CCW surface impoundments, but it is reasonable to assume that a sediment layer would accumulate and restrict flow from the bottom of a CCW impoundment.

- **Distance to the Nearest Surface Water Body.** The distance to the nearest waterbody is used to determine the location of a fully penetrating surface waterbody at which groundwater mass and water fluxes will be calculated and reported. The distance to the nearest surface waterbody is also used as a surrogate for the distance to the nearest point at which the water table elevation is kept at a fixed value. That distance is used to calculate the estimated height of groundwater mounding underneath the impoundment to ensure that excessively high infiltration rates, which may be calculated for deep, unlined impoundments, do not occur. If necessary, the model reduces the infiltration rate to ensure the predicted water table does not rise above the ground surface. For the CCW sites, distance to surface water was sampled from an empirical distribution developed from aerial photo measurements at 59 coal-fired power plants with onsite landfills or surface impoundments (**Appendix C**).

- **Leachate Concentration.** The annual average leachate concentration is modeled as a constant concentration pulse with a defined duration. For a particular model run, the leachate concentration was assumed to be constant during the operation of the unit; there is no reduction in leachate concentration until the impoundment ceases operation. Leachate concentrations for CCW impoundments were obtained by waste type from surface impoundment porewater data from EPA's CCW Constituent Database, as described in **Appendix A**.

- **Source Leaching Duration.** For surface impoundments, the addition and removal of waste during the operational life period are more or less balanced, without significant net accumulation of waste. In the finite-source implementation used for CCW surface impoundments, the duration of the leaching period is assumed to be the same as the operational life of the surface impoundment. Based on industry data (see **Appendix B**) for CCW surface impoundments, EPA used a high-end (90th percentile) fixed surface impoundment operating life of 75 years. A high-end value was appropriate because CCW surface impoundments are typically closed with waste in place, while the surface impoundment source-term model assumes clean closure (waste removed). In addition, operating life is not a particularly sensitive parameter in this analysis: the difference between the 50th percentile value (40 years) and the 90th percentile value used (75 years) is less than a factor of two.

- **Liner Type, Thickness, Hydraulic Conductivity, and Leak Density.** The type of liner is used to calculate leachate flux from the impoundment. To assign one of the three liner scenarios to each facility in the EPRI survey (EPRI, 1997), EPA used the same crosswalk as for landfills (see Table 3-7). Attachment B-2 to **Appendix B** provides these assignments, along with the original EPRI liner type, for each CCW surface impoundment modeled.

As with IWEM (U.S. EPA, 2002b), clay liners were assumed to be 3 feet thick and to have a constant hydraulic conductivity of 10^{-7} cm/s, reflecting typical design specifications for clay liners. For composite liners, infiltration was assumed to result from defects (pin holes) in the geomembrane. The pin holes were assumed to be circular and uniformly sized (6 mm^2). The leak density was defined as the average number of circular pin holes per square meter and was

obtained from a study of industrial surface impoundment membrane liner leak rates by Tetra Tech (2001).

3.5.4 Surface Impoundment Model Outputs

For each year in the simulation, the surface impoundment source-term model uses the average annual leachate concentration and calculates an infiltration rate to estimate the constituent flux through the bottom of the impoundment. This time series was used as an input to the EPACMTP unsaturated zone model.

3.6 Groundwater Model

This section describes the methodology and the models that were used to predict the fate and transport of chemical constituents in soil and groundwater to determine impacts on drinking water wells and surface water that is connected to groundwater. The surface water model used to address the groundwater-to-surface water pathways is described in **Section 3.7**.

3.6.1 Conceptual Model

The groundwater pathway was modeled to determine the receptor well concentrations and contaminant flux to surface water resulting from the release of waste constituents from a WMU. The release of a constituent occurs when liquid percolating through the WMU becomes leachate as it infiltrates from the bottom of the WMU into the subsurface. For landfills, the liquid percolating through the landfill is from water in the waste and precipitation. For surface impoundments, the percolating liquid is primarily the wastewater managed in the impoundments.

Waste constituents dissolved in the leachate are transported through the unsaturated zone (the soil layer under the WMU) to the underlying saturated zone (i.e., groundwater). Once in the groundwater, contaminants are transported downgradient to a hypothetical receptor well or waterbody. For this analysis, the groundwater concentration was evaluated for two receptor locations, each at a specified distance from the downgradient edge of the WMU:

- The intake point of a hypothetical residential drinking water well (the receptor well), which was used for the residential drinking water pathway
- A nearby river, stream, or lake, which is modeled as a fully penetrating surface waterbody and was used for the fish ingestion and ecological pathways.

Figure 3-6 shows the conceptual model of the groundwater fate and transport of contaminant releases from a WMU to a downgradient receptor well.

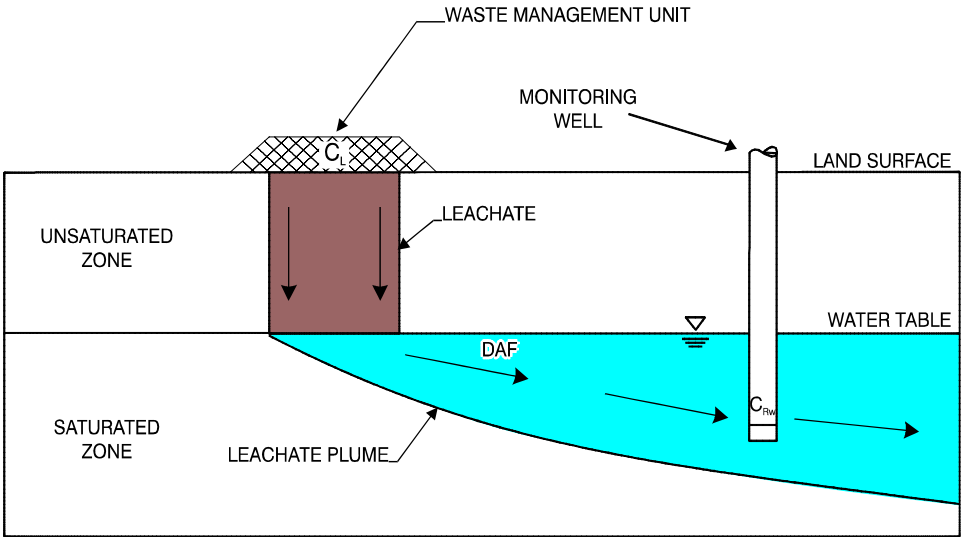


Figure 3-6. Conceptual model of the groundwater modeling scenario.

3.6.2 Modeling Approach and Assumptions

The transport of leachate from the WMU through the unsaturated and saturated zones was modeled using EPACMTP (U.S. EPA, 1996a, 1997a, 2003a,c,d). EPACMTP is a composite model consisting of two coupled modules: (1) a one-dimensional module that simulates infiltration and dissolved contaminant transport through unsaturated soils, and (2) a 3-dimensional saturated zone flow and transport module to model groundwater fate and transport. EPACMTP has been used by EPA to make regulatory decisions for wastes managed in land disposal units (including landfills and surface impoundments) for a number of solid waste and hazardous waste regulatory efforts, and as noted earlier, has undergone extensive peer review. EPACMTP simulates the concentration arriving at a specified receptor location (such as a well or stream).

The primary subsurface transport mechanisms modeled by EPACMTP are (1) downward (1-dimensional) movement along with infiltrating water flow in the unsaturated zone soils and (2) movement and dispersion along with ambient groundwater flow in the saturated zone. EPACMTP models soils and aquifer as uniform porous media and does not account for preferential pathways such as fractures and macropores or for facilitated transport, which may affect migration of strongly sorbing constituents such as metals.

In the unsaturated zone, flow is gravity driven and prevails in the downward direction. Therefore, the flow is modeled in the unsaturated zone as one-dimensional in the vertical direction. The model also assumes that transverse (sideways) dispersion (from both mechanical and molecular diffusion processes) is negligible in the unsaturated zone because the scale of lateral migration due to transverse dispersion is negligible compared with the size of the WMUs. This assumption is also environmentally protective because it allows the leading front of the contaminant plume to arrive at the water table with greater peak concentration in the case of a finite source.

In the saturated zone, the EPACMTP model assumes that movement of chemicals is driven primarily by ambient groundwater flow, which in turn is controlled by a regional hydraulic gradient and hydraulic conductivity in the aquifer formation. The model does take into account the effects of infiltration through the WMU, as well as regional recharge into the aquifer around the WMU. Infiltration through the WMU increases the groundwater flow in all directions under and near the WMU and may result in groundwater mounding. This 3-dimensional flow pattern enhances the horizontal and vertical spreading of the contaminant plume. The effect of recharge (outside the WMU) is to cause a downward (vertical) movement of the contaminant plume as it travels along groundwater flow direction. In addition to advective movement with the groundwater flow, the model simulates mixing of contaminants with groundwater due to hydrodynamic dispersion, which acts along the groundwater flow direction, as well as vertically and in the horizontal transverse direction.

To model sorption of CCW constituents in the unsaturated zone, soil-water partitioning coefficients (K_d values) for metal constituents were selected from nonlinear sorption isotherms generated from the equilibrium geochemical speciation model MINTEQA2 (U.S. EPA, 2001a). Chemicals with low K_d values will have low retardation factors, which means that they will move at nearly the same velocity as the groundwater. Chemicals with high K_d values will have high retardation factors and may move many times slower than groundwater. As described in **Appendix D**, CCW-specific partition coefficients were developed with MINTEQA2 considering CCW leachate chemistry, including the highly alkaline chemistries that are characteristic of some CCWs. Although a complete listing of all K_d values available in the MINTEQA2 isotherms used in these analyses would not be practicable, Table D-1 presents a sampling of the K_d values used.

MINTEQA2 is a product of ORD, and like EPACMTP, has a long history of peer- and SAB-review during its development, use, and continued improvement for regulatory support over the past two decades. These reviews largely focused on the use of MINTEQA2 to generate sorption isotherms for metals for EPACMTP, which is how it was used in the CCW risk assessment. Two of the more recent peer reviews include one for application within the 3MRA model (U.S. EPA, 1999d) and a review of its use and application to RCRA rulemaking and guidance support, including revisions made to the model to support IWEM and the CCW rulemaking efforts (U.S. EPA, 2003f). In the latter review, three experts found that the revisions made to the MINTEQA2 model were appropriate, but also suggested further improvements in how the model addresses environments with highly alkaline leachate (such as CCW sites). As explained in **Appendix D**, these comments were addressed in this application of MINTEQA2 to CCW waste transport by the development of sorption isotherms that are specific to geochemical conditions encountered in CCW landfills and surface impoundments.

3.6.3 Model Inputs and Receptor Locations

EPACMTP requires information about soil and aquifer properties as model inputs. For soils, EPACMTP uses soil texture to generate consistent hydrological properties for the unsaturated zone model, and soil pH and organic matter to select appropriate sorption coefficients to model contaminant sorption in the soil. As described in **Appendix C, Attachment C-2**, site-specific soil texture, pH, and organic carbon data were collected around each site from the STATSGO soils database. Similarly, the hydrogeological setting around each

WMU was used to select appropriate aquifer conditions from EPACMTP's Hydrogeologic Database (HGDB; see **Appendix C**).

Recharge is water percolating through the soil to the aquifer outside the footprint of the WMU. The recharge rate is determined by precipitation and soil texture. For the CCW landfills and surface impoundments, recharge rates were selected by soil texture and meteorological station assignment from a database of HELP model–derived recharge rates for climate stations across the country that is included in the EPACMTP input files. Further details about how these rates were determined and other options for determining recharge rates outside of the EPACMTP model can be found in the *EPACMTP Parameters/Data Background Document* (U.S. EPA, 2003a).

One of the most important inputs for EPACMTP is receptor location, which for this risk assessment includes residential drinking water wells and surface water bodies. **Figure 3-7** shows a schematic of how residential well drinking water intakes were defined in terms of their radial downgradient distance from the WMU and the angle off the contaminant plume centerline. The shaded areas in Figure 3-7 represent the horizontal extent of the contaminant plume.

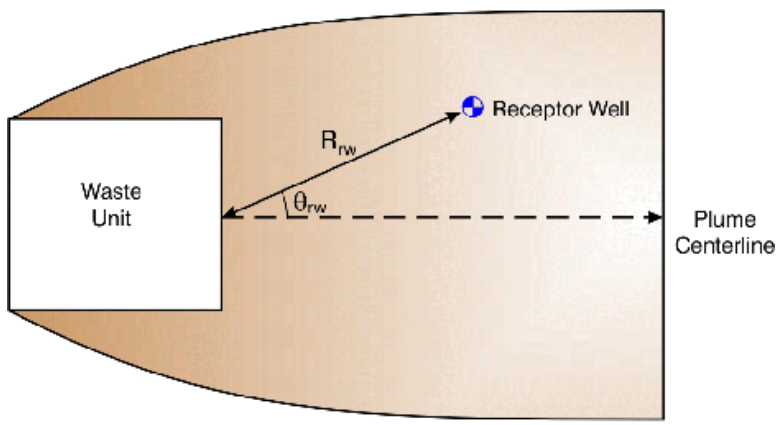


Figure 3-7. Schematic plan view showing idealized maximum lateral contaminant plume extent and receptor well location.

In this analysis, receptor wells were located randomly within the contaminant plume, as follows:

- Because residential well distance data are not available for CCW WMUs, EPA based the radial downgradient distance on a nationwide distribution of the nearest downgradient residential or municipal wells from a survey of Subtitle D municipal solid waste landfills (U.S. EPA, 1988a; see **Appendix C**). The maximum radial distance in this survey was 1 mile. EPA believes that this distribution is protective of CCW WMUs. A well distance, (R_{rw} in Figure 3-7) was randomly selected from this distribution.

- The angle off the contaminant plume centerline (θ_{rw} in Figure 3-7) was selected from a uniform distribution ranging from 0 to 90 degrees.

- The receptor well was located based on R_{rw} and θ_{rw} as shown in Figure 3-7.
- The maximum lateral extent of a groundwater plume, based on lateral dispersion, was calculated using the dimensions of the WMU sampled for that simulation, a sampled value for lateral dispersivity in the groundwater, and the downgradient distance to the receptor well.
- If the receptor well was located *inside* the idealized maximum plume extent, the shaded portion in Figure 3-7 (the distance from the well to the centerline was less than the lateral extent of the calculated in the previous step), the well location was used for that simulation. Otherwise, new values for R_{rw} and θ_{rw} were sampled and the process repeated for the same WMU. The depth of the well intake point was based on a uniform distribution with limits of 0 (i.e., well at the water table) to 10 meters (or the total saturated aquifer thickness if the aquifer is less than 10 meters thick).

The location of the surface waterbody intercepting groundwater flow was specified for each flow and transport simulation. The waterbody was constrained to lie across the contaminant plume centerline and perpendicular to the groundwater flow direction. The waterbody is assumed to fully penetrate the aquifer thickness. Downgradient distance to the surface waterbody was determined from an empirical distribution of distances measured for CCW landfills and surface impoundments (see **Appendix C**), which was randomly sampled to develop the distances used in EPACMTP to calculate groundwater concentrations at those distances in the Monte Carlo analysis.

3.6.4 Groundwater Model Outputs

The output of EPACMTP is a prediction of the contaminant concentration arriving at a downgradient groundwater receptor location (either a well or a surface water body). Because a finite-source scenario was used, the concentration is time-dependent. A maximum time-averaged concentration was calculated for each constituent across the exposure duration selected in each Monte Carlo iteration.

3.7 Surface Water Models

For the groundwater-to-surface-water pathway, chemical contaminants leach out of WMUs and into groundwater, and this contaminated groundwater then discharges into a surface waterbody through groundwater discharge. Once in the waterbody, the continued fate and transport of the contaminants is modeled with a surface water model, which uniformly mixes the contaminants in a single stream segment. Surface water flows in and out of the stream segment. Surface water flowing into the stream segment is assumed to have zero constituent concentration, and surface water flowing out has nonzero constituent concentrations due to the groundwater contamination. The primary simplifying assumptions in EPACMTP are as follows: (1) the groundwater–surface water interface is assumed to be perpendicular to the regional groundwater flow direction; (2) the interface is infinite in its lateral extent so as to intercept the entire width of the dissolved contaminant plume; and (3) the intercepting surface water body fully penetrates the saturated region of the subsurface. Therefore, all of the mass in the contaminated groundwater is available to be transferred to the surface water model. If stream

flow is greater than the available groundwater flow, then all of the mass available in the groundwater is assumed to be transferred to the surface waterbody. It is important to note that while a mass transfer is assumed to take place between the two systems, mass is not actually removed from the groundwater—it is still available to be observed at a receptor well placed beyond the groundwater-surface water interface.

To ensure that an unrealistic transfer of mass from the contaminated groundwater into the surface waterbody does not occur, the available groundwater flow is compared to the stream flow. If the groundwater flow exceeds the stream flow, all of the stream flow is assumed to be from groundwater discharge and the total concentration in the stream is equal to the groundwater concentration.

The waterbody considered in the CCW risk assessment is a river, stream, or lake located downgradient of the WMU. As described in **Appendix C**, the flow characteristics and dimensions for this waterbody were determined by site-specific stream flow data, the width of the groundwater contaminant plume as it intersects the waterbody, and established relationships between flow and stream depth. The stream segment modeled in this assessment was assumed to be homogeneously mixed.

Simple equilibrium partitioning models were used to estimate contaminant concentrations in the water column, suspended and bed sediments (see **Section 3.7.1**), and aquatic organisms (see **Section 3.7.2**). Special modeling provisions for aluminum are described in **Section 3.7.3**.

3.7.1 Equilibrium Partitioning Model

The primary surface water model used to estimate groundwater impacts on waterbodies is a simple steady-state equilibrium-partitioning model adapted from models in EPA's Indirect Exposure Methodology (IEM; U.S. EPA, 1998c) and Human Health Risk Assessment Protocol (HHRAP; U.S. EPA, 1998d). This model is based on the concept that dissolved and sorbed concentrations can be related through equilibrium partitioning coefficients. This model was used for all constituents except aluminum, which was modeled based on a solubility approach (see **Section 3.7.3**). Although these models have not been specifically peer reviewed in this application, they have been subject to the Agency's peer review process as part of the development of the IEM and HHRAP.

The model partitions the total mass of chemical contaminant in the waterbody into four compartments:

- Constituents dissolved in the water column
- Constituents sorbed onto suspended solids
- Constituents sorbed onto sediment particles at the bottom of the waterbody
- Constituents dissolved in porewater in the sediment layer.

Table 3-9 provides the partitioning coefficients used by the surface water model to estimate contaminant partitioning between water and suspended solids in the water column and between

sediment and porewater in the sediment layer. These distributions were derived from published empirical data as described in U.S. EPA (1999b).

Table 3-9. Sediment/Water Partition Coefficients: Empirical Distributions[a]

Chemical	Distribution Type	Minimum	Mean	Maximum	SD
Aluminum	not used				
Antimony	log normal	0.6	3.6	4.8	1.8
Arsenic	log normal	1.6	2.4	4.3	0.7
Barium	log normal	0.9	2.5	3.2	0.8
Boron	log normal	−0.5	0.8	1.4	0.5
Cadmium	log normal	0.5	3.3	7.3	1.8
Cobalt	log normal	2.2	3.9	5.3	0.8
Lead	log normal	2.0	4.6	7.0	1.9
Molybdenum	log normal	1.3	2.2	3.2	0.9
Selenium IV	log normal	1.0	3.6	4.0	1.2
Selenium VI	log normal	−1.4	0.6	3.0	1.2
Thallium	log normal	−0.5	1.3	3.5	1.1
Total Nitrate Nitrogen	constant	0	0	0	0

Source: U.S. EPA (1999b).
SD = standard deviation.
[a] All values are log values.

Following calculation of the constituent loading and loss rates, the surface water model estimates steady-state, equilibrium waterbody contaminant concentrations in each compartment using equations presented in Attachment E-1 to **Appendix E**. For evaluating risks to human health from fish consumption, the model calculates waterbody concentrations using groundwater loadings that are explicitly averaged over the exposure period for the each human receptor (i.e., adult and child fishers). These average waterbody concentrations are then used to calculate fish concentrations as described in **Section 3.7.2**. Ecological risks were based on waterbody concentrations calculated using the peak annual groundwater loading value from EPACMTP. The equilibrium–partitioning model, as implemented, is conservative because there are no loss mechanisms (e.g., burial) for any of the constituents.

3.7.2 Aquatic Food Web Model

An aquatic food web model was used to estimate the concentration of CCW constituents that accumulate in fish. This risk assessment assumed that fish are a food source for a recreational fisher. Trophic level three (TL3) and four (TL4) fish[12] were considered in this analysis because most of the fish that humans eat are T4 fish (e.g., salmon, trout, walleye, bass) and medium to large T3 fish (e.g., carp, smelt, perch, catfish, sucker, bullhead, sauger). The aquatic food web model has been peer reviewed as part of the 3MRA model development effort (see http://www.epa.gov/osw/hazard/wastetypes/wasteid/hwirwste/peer03/aquatic/aqtfoods.pdf).

[12] TL3 fish are those that consume invertebrates and plankton; TL4 fish are those that consume other fish.

The aquatic food web model calculates the concentration in fish from the concentration calculated for the waterbody downgradient from the CCW disposal site. The contaminants in the water column consist of dissolved constituents and constituents sorbed to suspended solids. For all constituents, the contaminant concentrations in fish were calculated from the total waterbody concentration (i.e., dissolved plus sorbed to suspended solids) using BCFs, which are presented in **Table 3-10**. The equations used to model fish tissue concentrations are provided in Attachment E-2 to **Appendix E**.

Table 3-10. Bioconcentration Factors for Fish

CAS	Chemical	TL3 Value	TL4 Value	Units	Reference
7429-90-5	Aluminum	ND	ND	L/kg	
7440-36-0	Antimony	0	0	L/kg	Barrows et al. (1980)
22569-72-8	Arsenic (III)	4.0E+00	4.0E+00	L/kg	Barrows et al. (1980)
15584-04-0	Arsenic (V)	4.0E+00	4.0E+00	L/kg	Barrows et al. (1980)
7440-39-3	Barium	ND	ND	L/kg	
7440-42-8	Boron	ND	ND	L/kg	
7440-43-9	Cadmium	2.7E+02	2.7E+02	L/kg	Kumada et al. (1972)
7440-48-4	Cobalt	ND	ND	L/kg	
7439-92-1	Lead	4.6E+01	4.6E+01	L/kg	Stephan (1993)
7439-98-7	Molybdenum	4.0E+00	4.0E+00	L/kg	Eisler (1989)
10026-03-6	Selenium (IV)	4.9E+02	1.7E+03	L/kg	Lemly (1985)
7782-49-2	Selenium (VI)	4.9E+02	1.7E+03	L/kg	Lemly (1985)
7440-28-0	Thallium	3.4E+01	1.3E+02	L/kg	T3: Barrows et al. (1980) T4: Stephan (1993)
14797-55-8	Total Nitrate Nitrogen	ND	ND	L/kg	

ND = No Data. Fish concentrations were not calculated for constituents with no BCF data.

3.7.3 Aluminum Precipitation Model

Aluminum is generally solubility limited in natural waters; therefore, a simple precipitation model was used for aluminum in lieu of the equilibrium-partitioning model. The MINTEQA2 model was used to estimate total soluble aluminum concentrations as a function of pH for a typical surface waterbody (Stumm and Morgan, 1996; Drever, 1988). By assuming the common aluminum silicate mineral gibbsite was the equilibrium solid phase, the computed values of total dissolved aluminum were interpreted as the maximum expected for each pH. If more aluminum were added to the system, it would be expected to precipitate as the mineral gibbsite for the system to maintain equilibrium. **Table 3-11** shows the maximum dissolved aluminum concentrations as a function of waterbody pH.

The precipitation model initially calculates the aluminum concentration in the surface water column by assuming that all aluminum in the groundwater flux is dissolved. If this concentration exceeds the maximum soluble concentration based on pH, the dissolved concentration is capped and the excess aluminum is assumed to precipitate as the mineral gibbsite and settle to the benthic sediment layer. The equations used in this model are presented in **Appendix E**.

Table 3-11. Aluminum Solubility as a Function of Waterbody pH[a]

Minimum pH	Maximum pH	Solubility (mg/L)
3.5	4.5	26.2
4.5	5	1.84
5	5.5	0.196
5.5	6	0.0112
6	6.5	0.00143
6.5	7	0.000662
7	7.5	0.000915
7.5	8	0.00229
8	8.5	0.00682
8.5	9	0.0212
9	9.5	0.0666
9.5	10	0.211
10	10.5	0.668

[a] Computed using MINTEQA2

Only the water column concentration for aluminum was used in subsequent exposure and risk calculations, because there is no available ecological benchmark for aluminum in sediment. The water column concentration was used to calculate human exposure via drinking water ingestion, as well as risk to ecological receptors exposed via direct contact.

3.8 Human Exposure Assessment

The human exposure component of the full-scale analysis assessed the magnitude, frequency, duration, and route of exposure to CCW contaminants that an individual may experience. The term “exposure,” as defined by the EPA exposure guidelines (U.S. EPA, 1992), as the condition that occurs when a contaminant comes into contact with the outer boundary of the body. The exposure of an individual to a contaminant completes an exposure pathway (i.e., the course a constituent takes from the WMU to an exposed individual). Once the body is exposed, the constituent can cross the outer boundary and enter the body. The amount of contaminant that crosses and is available for adsorption at internal exchange boundaries is referred to as the “dose” (U.S. EPA, 1992).

This risk assessment evaluated the risk from CCW contaminants to receptors in the vicinity of a WMU. The individuals evaluated were those residents closest to the WMU. The distances from the WMU to the residents were taken from a distribution of distances to the nearest residential drinking water well measured for municipal landfills and, for the recreational fisher, a distribution of the distance of the nearest surface water body from CCW landfills and surface impoundments (see **Appendix C**).

Section 3.8.1 presents an overview of the receptors and selected exposure pathways considered for this assessment, including a discussion of how childhood exposure was considered in the analysis. **Section 3.8.2** presents exposure factors (i.e., values needed to calculate human exposure) used in the analysis. **Section 3.8.3** describes the methods used to estimate dose, including average daily dose (ADD) and lifetime average daily dose (LADD).

3.8.1 Receptors and Exposure Pathways

Human receptors may come into contact with constituents present in environmental media through a variety of pathways. The exposure pathways considered in the full-scale analysis were ingestion of drinking water from contaminated groundwater sources and ingestion of fish from surface water contaminated by groundwater.

- **Ingestion of Drinking Water.** Groundwater from an offsite well was assumed to be used for drinking water for residents (adult and child).
- **Ingestion of Fish.** Fish are exposed to constituents via uptake of contaminants from surface water. Adult recreational fishers and their children were assumed to consume fish caught in local waterbodies contaminated by CCW constituents through the groundwater-to-surface-water pathway. EPA considers this assumption to be reasonable and protective for fishers relying on locally caught fish as a food source.

Table 3-12 lists each human receptor type considered in this analysis along with the specific exposure pathways that apply to that receptor. Both adult and child residents are exposed by drinking groundwater, and adult fishers and their children are exposed by eating fish caught in streams and lakes impacted by CCW.

Table 3-12. Receptors and Exposure Pathways

Receptor	Ingestion of Drinking Water	Ingestion of Fish
Adult resident	✓	
Child resident	✓	
Adult recreational fisher		✓
Child of recreational fisher		✓

Children are an important subpopulation to consider in a risk assessment because they may be more sensitive to exposures than adults. Compared with adults, children may eat more food and drink more fluids per unit of body weight. This higher intake-rate-to-body-weight ratio can result in a higher ADD for children than adults.

As children mature, their physical characteristics and behavior patterns change. To capture these changes in the analysis, the life of a child was considered in stages represented by the following cohorts: cohort 1 (ages 1 to 5), cohort 2 (ages 6 to 11), cohort 3 (ages 12 to 19), and cohort 4 (ages 20 to 70). Associated with each cohort are distributions of exposure parameters that reflect the physical characteristics and behavior patterns of that age range. These exposure parameters are required to calculate exposure to an individual. The distributions for the 20- to 70-year-old cohort were the same as those used for adult receptors.

To capture the higher intake-rate-to-body-weight ratio of children, a start age of 1 year was selected for the child receptors. The exposure duration distribution for cohort 1 (a 1- to 5-year-old) was used to define exposure duration for the child receptors for each of the 10,000 iterations in the probabilistic analysis. For each individual iteration, the child receptor was aged through the age cohorts as appropriate until the age corresponding to the selected exposure duration was reached (e.g., if an exposure duration of 25 years was selected for an iteration, the

child was aged from 1 year to 25 years, spending 5 years in cohort 1, 6 years in cohort 2, 8 years in cohort 3, and 6 years in cohort 4, for a total of 25 years).

3.8.2 Exposure Factors

The exposure factors used in the risk assessment are listed in **Table 3-13**, along with their data sources and variable type (i.e., whether they were represented as a distribution or a fixed value in the Monte Carlo analysis). These exposure factors were used to calculate the dose of a chemical based on contact with contaminated media or food, the duration of that contact, and the body weight of the exposed individuals.

Table 3-13. Human Exposure Factor Input Parameters and Data Sources

Parameter	Variable Type	Data Source
Body weight (adult, child)	Distribution	U.S. EPA (1997c)
Ingestion rate: fish (adult, child)	Distribution	U.S. EPA (1997d)
Ingestion rate: drinking water (adult, child)	Distribution	U.S. EPA (1997c)
Exposure duration (adult, child)	Distribution	U.S. EPA (1997e)
Exposure frequency (adult, child)	Fixed (constant)	U.S. EPA policy
Fraction contaminated: drinking water	Fixed (constant)	U.S. EPA policy
Fraction contaminated: fish	Fixed (constant)	U.S. EPA policy
Fraction of TL3 fish consumed	Fixed (constant)	U.S. EPA (1997d)
Fraction of TL4 fish consumed	Fixed (constant)	U.S. EPA (1997d)
Human lifetime (used in carcinogenic risk calculation)	Fixed (constant)	U.S. EPA policy

The primary data source of human exposure model inputs used in this risk assessment was EPA's *Exposure Factors Handbook* (EFH; U.S. EPA, 1997c-e). The EFH summarizes data on human behaviors and characteristics related to human exposure from relevant key studies and provides recommendations and associated confidence estimates on the values of exposure factors. These data were carefully reviewed and evaluated for quality before being included in the EFH. EPA's evaluation criteria included peer review, reproducibility, pertinence to the United States, currency, adequacy of the data collection period, validity of the approach, representativeness of the population, characterization of variability, lack of bias in study design, and measurement error (U.S. EPA, 1997c-e). For exposure factors that were varied in the Monte Carlo analysis, probability distribution functions were developed from the values in the EFH.

The data sources and assumptions for intake and other human exposure factors used in this analysis are described below. **Appendix F** presents the exposure factors used and describes the rationale and data used to select the form of the distributions (e.g., normal, lognormal, gamma, Weibull) for those exposure factors that were varied in the probabilistic analysis. Data for three child cohorts (ages 1–5, 6–11, and 12–19 years) and adults were used. However, as most infants are breastfed and therefore are not exposed to fish or water, they were excluded from the risk assessment (i.e., modeling start age for a child is 1 year).

- **Body Weight.** Distributions of body weight were developed for adult and child receptors based on data from the EFH.

- **Fish Ingestion Rate.** Fish ingestion rates were based on a recreational angler who catches and eats some fish from a waterbody impacted by contaminants released from CCW WMUs. Distributions of fish intake rates were developed for adult fishers based on data from the 1997 EFH. At the time the risk assessment was conducted (May-June 2003), separate fish ingestion rates for children of recreational anglers were not available.

- **Drinking Water Ingestion Rate.** Distributions of drinking water intake rates were developed for the adult and child resident based on data from the EFH.

- **Exposure Duration.** Exposure duration refers to the amount of time that a receptor is exposed to a contaminant source. Exposure duration was assumed to correspond with the receptor's residence time in the same house. Exposure durations were determined using data on residential occupancy from the EFH. The data used to develop parameter information for resident receptors were age-specific. Thus, separate exposure duration distributions were developed for adult and child residents. For children, the modeling start age is 1 year, and exposure duration was used to determine the amount of time spent in each cohort (e.g., if exposure duration was 2 years, consumption rates and body weights were based only on cohort 1 data; however, if exposure duration was 21 years, the child spends 5 years in cohort 1, 6 years in cohort 2, 8 years in cohort 3, and 2 years in cohort 4/adult). Infants between birth and 1 year are not modeled because they are assumed to either breastfeed or consume commercial formula.

- **Exposure Frequency.** Exposure frequency is the frequency with which the receptor is exposed to the contaminated source during the exposure duration. Exposure frequency is not expected to vary much, so distributions were not developed for exposure frequency. All receptors were assumed to be exposed to the contaminant source 350 days/year. This value was based on the assumption that individuals are away from their homes (e.g., on vacation) approximately 2 weeks out of the year, but are otherwise exposed daily.

- **Lifetime and Averaging Time.** Averaging time is the period of time over which a receptor's dose is averaged. To evaluate carcinogens, total dose was averaged over the lifetime of the individual, assumed to be 70 years. To evaluate noncarcinogens, dose was averaged over the last year of exposure because noncancer effects may become evident during less-than-lifetime exposure durations if toxic thresholds are exceeded. Essentially, this amounts to setting exposure duration and averaging time equal so that they cancel each other out in the equation for ADD. Thus, neither exposure duration nor averaging time is included in the ADD equation.

3.8.3 Dose Estimates

An exposure assessment estimates the dose to each receptor from the contaminant concentration in the exposure medium (e.g., drinking water, fish) and the intake rate for that medium (e.g., ingestion rate of drinking water, ingestion rate of fish). For this assessment, exposure estimates were based on the *potential* dose (e.g., the dose ingested) rather than the *applied* dose (e.g., the dose delivered to the gastrointestinal tract) or the *internal* dose (e.g., the dose delivered to the target organ). Doses from groundwater or fish ingestion were calculated by multiplying the contaminant concentration in groundwater or fish by the respective intake rate on

a per kilogram body weight basis. Doses were then summed over the exposure duration, resulting in an ADD received from ingestion exposure. The ADD was used to assess noncancer risk from ingestion exposures and is defined as

$$ADD = C \times IR \tag{3-2}$$

where

C = average concentration (mass/volume or mass/mass)
IR = intake rate (mass/body weight mass/time, or volume/body weight mass/time).

Contaminant concentration represents the concentration of a chemical in a medium that contacts the body. The ADD was calculated from concentrations averaged over the exposure duration for each receptor.

For cancer effects, where the biological response is described in terms of lifetime probabilities even though exposure may not occur over the entire lifetime, dose is presented as a LADD. The LADD was used to assess cancer risks from each exposure route (i.e., ingestion) and is defined as

$$LADD = \frac{C \times IR \times ED \times EF}{AT \times 365} \tag{3-3}$$

where

C = average concentration (mass/mass or mass/volume)
IR = intake rate (mass/body weight mass/time, or volume/body weight mass/time)
ED = exposure duration (yr)
EF = exposure frequency (d/yr)
AT = averaging time (yr)
365 = units conversion factor (d/yr).

As with the ADD, contaminant concentration represents the concentration of a chemical in a medium that contacts the body. Intake rate depends on the route of exposure; for example, it might be an inhalation rate or an ingestion rate. Exposure frequency is the number of days per year the receptor is exposed to the contaminated source during the exposure duration.

For cancer effects, biological responses are described in terms of lifetime probabilities, even though exposure may not be lifelong; consequently, the exposure duration (the length of time of contact with a contaminant) was used to average the ADD over a lifetime (70 years). The media concentrations used were averaged over the duration of exposure.

3.9 Risk Estimation

The final step of the risk assessment process is to estimate the risk posed to human and ecological receptors (e.g., residents, fishers; aquatic organisms). In this step, estimates of toxicity

(the human health and ecological benchmarks) and exposure doses or exposure concentrations are integrated into quantitative expressions of risk. For the CCW constituents modeled in the full-scale assessment, the CCW human risk assessment used estimates of dose and toxicity to calculate individual excess lifetime carcinogenic risk estimates and noncancer HQs (**Section 3.9.1**). The risk calculations for ecological receptors differ from those for humans because the ecological benchmarks are developed as media concentrations (i.e., they are calculated considering ecological exposure). Thus the CCW risk assessment used estimates of exposure (media) concentrations and toxicity (media-specific concentration limits) to calculate an ecological HQ (**Section 3.9.2**).

3.9.1 Human Health Risk Estimation

The full-scale analysis focused on two human health exposure pathways: groundwater-to-drinking-water and groundwater-to-surface-water via fish consumption by recreational fishers. The cancer and noncancer health impacts of ingesting groundwater and fish contaminated by CCW leachate were estimated using the risk endpoints shown in **Table 3-14**. These endpoints were generated for each iteration of the Monte Carlo analysis. Only the cancer endpoint was used for arsenic, because it is the more sensitive endpoint compared to noncancer effects. For the other 11 constituents, only noncancer HQs were calculated, using the appropriate noncancer endpoint.

Table 3-14. Risk Endpoints Used for Human Health

Risk Category	Risk Endpoints	Definition
Cancer Effects (arsenic only)	Lifetime excess cancer risk by pathway and chemical	Lifetime excess cancer risk resulting from single pathway exposure
Noncancer Effects	Ingestion HQ by pathway and chemical	Ingestion HQ resulting from single pathway exposure
	Ingestion HQ based on drinking water action level for lead and copper	Lead and copper ingestion HQ resulting from drinking water pathway
	Average daily dose for fish consumption for lead	Lead exposure resulting from fish ingestion pathway

Cancer risks for arsenic were characterized using lifetime excess cancer risk estimates, which represent the excess probability of developing cancer over a lifetime as a result of exposure to the chemical of interest. Lifetime excess cancer risk estimates use the LADD (see **Section 3.8.3**) as the exposure metric. Lifetime excess cancer risk estimates are the product of the LADD for a specific receptor and the corresponding cancer slope factor, as shown in Equation 3-4.

$$Lifetime\ excess\ cancer\ risk_i = LADD_i \times CSF \qquad (3\text{-}4)$$

where

LADD = lifetime average daily dose for ingestion pathway i (mg/kg BW/d)
i = pathway index
CSF = cancer slope factor $(mg/kg\ BW/d)^{-1}$.

Noncancer risk was characterized through the use of HQs, which are generated by dividing an ADD (see **Section 3.8.3**) for ingestion pathways by the corresponding RfD.[13] An HQ establishes whether a particular individual has experienced exposure above a threshold for a specific health effect. Therefore, unlike cancer risk estimates, HQs are not probability statements. Rather, the RfD represents an estimate (with uncertainty spanning perhaps an order of magnitude) of a daily oral exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime. It can be derived from a no observed adverse exposure level (NOAEL), lowest observed adverse exposure level (LOAEL), or benchmark dose, with uncertainty factors generally applied to reflect limitations of the data used. Equation 3-5 shows the calculation for the ingestion HQ. This calculation was completed for each pathway considered (i.e., drinking water ingestion and fish consumption).

$$HQ_i = \frac{ADD_i}{RfD} \tag{3-5}$$

where

ADD_i = average daily dose for ingestion pathway i (mg/kg-d)
i = pathway index
RfD = reference dose (mg/kg-d).

The risk results address risk from exposure via the groundwater-to-drinking-water and groundwater-to-surface-water pathway separately. This is appropriate because the resident consuming contaminated groundwater may not be the recreational fisher who is consuming contaminated fish. Also, the arrival time of the contaminant plume to the stream and the human receptor may not be the same for a particular iteration.[14] However, a resident may consume fish caught from a nearby stream or lake and contaminated drinking water if the travel times are similar, so that possibility should be considered as an uncertainty in this analysis (see **Section 4.4.1**).

For each receptor type, lifetime excess cancer risk estimates for arsenic were calculated separately for the drinking water and fish consumption pathways.

3.9.2 Ecological Risk Estimation

The full-scale analysis addressed two routes of exposure for ecological receptors: direct contact with contaminated media and ingestion of contaminated food items. HQs were calculated using chemical-specific media concentrations assumed to be protective of ecological receptors of concern through either exposure route (CSCLs). As described in **Section 3.1.2**, these ecological benchmarks were developed for representative organisms and communities in each environmental medium of concern.

[13] HQs calculated for lead in drinking water were based on the drinking water action level (0.015 mg/L); lead exposures from fish ingestion are reported as an ADD.
[14] Stream distance and well distance were sampled independently in the Monte Carlo analysis.

For a particular Monte Carlo iteration, HQs were calculated for sediment and surface water as the ratio between the media concentration and the ecological benchmark. Because the CSCLs were derived for an HQ of 1 (for relevant ecological endpoints), the ratio of a constituent concentration in a media to the media-specific CSCL represents the HQ for that constituent and pathway. For surface water, the HQ was calculated as follows:

$$HQ_{surface\ water} = C_{sw} / CSCL_{sw} \tag{3-6}$$

where

C_{sw} = total concentration in surface water column (mg/L)
$CSCL_{sw}$ = ecological benchmark for surface water (mg/L).

Similarly, for sediment, the HQ was calculated as

$$HQ_{sediment} = C_{sediment} / CSCL_{sediment} \tag{3-7}$$

where

$C_{sediment}$ = total concentration in sediment (mg/kg)
$CSCL_{sediment}$ = ecological benchmark for sediment (mg/kg).

Because the sediment and surface water benchmarks were based on separate receptor communities, it is not appropriate to add HQs across pathways.

4.0 Risk Characterization

This section summarizes the results of the full-scale Monte Carlo analysis and characterizes those results in terms of significant uncertainties and the scenarios and factors that influence risks to human health and the environment. Results are presented at a high-end (90th percentile) and typical (50th percentile) exposure for both pathways under each combination of WMU type, ash type, and liner type.

An overview of the assessment on which these results were based (e.g., waste management scenarios, analysis framework) is provided in **Section 2**. **Section 3** provides more details on analysis methodologies, parameter values, and assumptions. In this section, **Section 4.1** presents results from the human health risk assessment and includes an analysis of how liner conditions influence results. **Section 4.2** presents the results from the ecological risk assessment. Tables summarizing the human and ecological results are presented in each section. **Section 4.3** describes the sensitivity analysis conducted for the CCW risk assessment, and **Section 4.4** discusses how variability and uncertainty have been addressed, including a semi-quantitative review of the potential impact of some of the more significant uncertainties on results.

The probabilistic results were based on a Monte Carlo simulation in which many model input parameter values were varied over 10,000 iterations of the model per waste management scenario to yield a statistical distribution of exposures and risks. Per the Guidance for Risk Characterization developed by the EPA Science Policy Council in 1995 (http://www.epa.gov/OSA/spc/pdfs/rcguide.pdf), EPA defined the high end of the risk distribution at the 90th percentile risk or hazard estimate generated during the Monte Carlo simulation. Thus, the 90th percentile risk results are shown in this section as the high-end estimate of the risk distribution generated during the Monte Carlo simulation of constituent release, fate and transport, and exposure associated with CCW disposal in landfills and surface impoundments. In addition, the 50th percentile results are presented as the central tendency estimate of that risk distribution.

For exposure scenarios describing the waste management unit type (e.g., lined landfill; unlined surface impoundment), waste type (e.g., conventional CCW, ash mixed with coal refuse), receptor (i.e., child, adult, ecological), and health endpoint (i.e., cancer, noncancer, ecological), the 90th percentile risk represents the high-end estimate of cancer or noncancer risk that was used to help determine whether CCW disposal practices are protective of public health. To evaluate the significance of the estimated cancer risks or noncancer hazards that are attributable to CCW disposal for the exposure pathways assessed in this assessment, EPA compared the risk estimates to a risk range (for carcinogens) or to a specific risk criterion (for noncarcinogens) that are protective of human health and the environment:

- An estimate of the excess lifetime cancer risk for individuals exposed to carcinogenic (cancer-causing) contaminants ranging from 1 chance in 1,000,000 (10^{-6} excess cancer risk) to 1 chance in 10,000 (10^{-4} excess cancer risk). For decisions made to screen out

certain constituents from further consideration, a 1 in 100,000 (10^{-5}) excess lifetime cancer risk) was used.[1]

- For constituents that cause adverse, noncancer health effects (noncarcinogens), the criterion is an HQ of greater than 1, with the HQ being the ratio of the average daily exposure level to a protective exposure level corresponding to the maximum level at which no appreciable effects are likely to occur.

- An HQ greater than 1 for was used to identify constituents with adverse effects to ecological receptors.

In general, the full-scale analysis showed lower risks than the screening analysis, but still showed risks within or above the cancer risk range or above an HQ of 1 for certain CCW constituents, WMU types, pathways, and receptors at the 90th percentile. At the 50th percentile, risks are still above these levels for both WMU types, but for fewer constituents and pathways. The results presented herein are subject to further interpretation, as EPA queries the CCW risk inputs and outputs to investigate how the results may be affected by (1) waste types and environmental and waste management conditions, (2) assumptions made about these conditions in designing the probabilistic analysis, and (3) the availability of newer facility data.

4.1 Human Health Risks

This section presents the 90th and 50th percentile risk results for the two human exposure pathways evaluated in the full-scale analysis: (1) groundwater-to-drinking-water and (2) groundwater-to-surface-water (fish consumption). Results are presented for the two WMU types addressed in the analysis: landfills and surface impoundments, and show the distribution of risks across all waste types by liner type from the EPRI survey data (see **Section 4.1.3** for further discussion of liners).

4.1.1 Groundwater-to-Drinking-Water Results by Waste Type/WMU Scenario

As described in **Section 3.3**, the CCW risk assessment was organized by waste type so that different waste chemistries could be accounted for in the fate and transport modeling. The results discussed so far in this report address conventional CCW (fly ash, bottom ash, boiler slag, FGD sludge) and conventional CCW codisposed with coal refuse.[2] **Section 4.1.1.1** presents these results by waste type. FBC wastes were also modeled in this assessment. However, there was a very small number of FBC waste disposal sites (seven) in the EPRI/EPA database. For this reason, the FBC results are treated separately in **Section 4.1.1.2**. Groundwater results are reported for a resident's child because these consistently led to higher HQs, with the exception of arsenic cancer values, which were consistently higher in adults. Thus, the cancer risks reported are for adults.

[1] The typical cancer risk range used by the Office of Solid Waste and Emergency Response is 10^{-4} to 10^{-6}.

[2] Coal refuse is the waste coal produced from coal handling, crushing, and sizing operations, and tends to have a high sulfur content and low pH. In the CCW constituent database, codisposed coal refuse includes "combined ash and coal gob," "combined ash and coal refuse," and "combined bottom ash and pyrites."

Note that only the chemicals for which constituent data were adequate to model and assess risks were modeled in the full-scale assessment, and only those modeled chemical/pathway/WMU scenarios are shown in the tables and figures. For example, antimony and thallium risks are not presented for surface impoundments and mercury is not shown for either landfills or surface impoundments because more than 90% of the measurements were nondetects. For further discussion of how nondetects were treated, see **Section 4.4.3.1**. Although screening-level human health risks for aluminum and barium were below the screening criteria, they were modeled in the risk assessment due to their potential to cause ecological harm. Additionally, there were nine constituents that failed the screen but were not modeled. Instead, these constituents were dealt with using risk attenuation factors, as described in **Section 4.1.4**. The screening analysis results in **Section 3.2.4** and **Table 3-6** show which CCW constituents were modeled.

Results for two constituents (arsenic and selenium) also varied based on chemical speciation. An earlier draft of this document showed results assuming 100% trivalent arsenic (arsenic III) and 100% hexavalent selenium (selenium VI) because these forms are more mobile in soil and groundwater, and thus would show higher estimated risks than either arsenic V or selenium IV. This revised draft also presents results for arsenic V and selenium IV. The results for the two species of arsenic and selenium bound the range of possible risks for these two constituents. For further discussion of speciation, see **Section 4.4.2**.

4.1.1.1 Conventional CCW and CCW Codisposed with Coal Refuse

Tables 4-1 and **4-2** show 90th and 50th percentile risk results, respectively, by waste type and liner type for CCW landfills for the drinking water pathway. Although some risks were higher for conventional CCW and others for codisposed CCW, there was generally little difference in results between waste types for landfills. Although risks are greater for unlined landfills than for clay-lined landfills, those with composite liners show zero, or near-zero, risks for all constituents modeled in this assessment (see **Section 4.1.3** for a further discussion of risks by liner type).

Tables 4-3 and **4-4** show the 90th and 50th percentile risk results, respectively, by waste type and liner type for CCW surface impoundments for the drinking water pathway. The difference in risks between waste types is greater for surface impoundments than for landfills. For surface impoundments, some constituents present higher risks from CCW managed alone (boron, molybdenum, nitrate, and selenium). However, others presented higher risks when CCW is comanaged with coal refuse (arsenic, cadmium, cobalt, and lead). This result is likely due to the higher metal concentrations and the acidity of coal refuse leachate[3] for surface impoundments in the CCW database, which in turn result from the association of these elements (and acidity) with the sulfide minerals[4] that are concentrated in coal refuse (Finkelman, 1995). As with landfills, clay-lined units show lower risks than unlined units, and composite liners show zero, or near-zero, risks for either waste type.

[3] Many metals tend to be more soluble and mobile in acidic leachate.
[4] Arsenic: pyrite, cadmium: sphalerite, lead: galena, cobalt: pyrite.

When viewing the results in Tables 4-1 through 4-4, readers should note that these risks assume that the contaminated groundwater plume will intercept a receptor well. Because approximately two-thirds of the model runs showed surface water bodies intersecting the groundwater plume, there could be a significant number of instances where a well is either not contaminated or is less contaminated than the results below would indicate. This uncertainty is discussed further in **Section 4.4.3.3**.

Table 4-1. 90th Percentile Risk Results by CCW Type: Landfills, Groundwater-to-Drinking-Water Pathway

Chemical	90th Percentile HQ or Cancer Risk Value[a]		
	Unlined Units	Clay-Lined Units	Composite-Lined Units
Conventional CCW – 79 landfills			
Cancer			
Arsenic III	4E-04	2E-04	0
Arsenic V	2E-04	3E-05	0
Noncancer			
Aluminum	2E-03	1E-04	0
Antimony	2	0.8	0
Barium	3E-03	7E-04	0
Boron	0.7	0.4	0
Cadmium	0.7	0.4	0
Cobalt	1	0.4	0
Lead (MCL)[b]	1	0.3	0
Molybdenum	2	0.8	0
Nitrate/nitrite (MCL)[b]	0.1	0.06	2E-06
Selenium IV	0.01	3E-3	0
Selenium VI	0.2	0.1	0
Thallium	3	2	0
Codisposed CCW and Coal Refuse – 41 landfills			
Cancer			
Arsenic III	5E-04	2E-04	0
Arsenic V	4E-04	6E-05	0
Noncancer			
Aluminum	0.02	4E-04	0
Antimony	0.8	0.3	0
Barium	0.04	4E-03	0
Boron	0.3	0.1	0
Cadmium	0.2	0.07	0
Cobalt	0.8	0.09	0
Lead (MCL)[b]	0.7	0.09	0
Molybdenum	2	0.6	0

(continued)

90th Percentile Risk Results by CCW Type: Landfills, Groundwater-to-Drinking-Water Pathway (continued)

Chemical	90th Percentile HQ or Cancer Risk Value[a]		
	Unlined Units	Clay-Lined Units	Composite-Lined Units
Nitrate/nitrite (MCL)[b]	0.2	0.1	3E-06
Selenium IV	0.1	0.04	0
Selenium VI	0.7	0.3	0
Thallium	2	1	0

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.
[b] Values are ratios of exposure concentration to MCL.

Table 4-2. 50th Percentile Risk Results by CCW Type: Landfills, Groundwater-to-Drinking-Water Pathway

Chemical	50th Percentile HQ or Cancer Risk Value[a]		
	Unlined Units	Clay-Lined Units	Composite-Lined Units
Conventional CCW – 79 landfills			
Cancer			
Arsenic III	6E-06	4E-06	0
Arsenic V	6E-10	3E-14	0
Noncancer			
Aluminum	5E-07	3E-07	0
Antimony	0.04	0.02	0
Barium	0	0	0
Boron	0.01	0.01	0
Cadmium	0.01	8E-03	0
Cobalt	3E-03	8E-06	0
Lead (MCL)[b]	4E-04	2E-08	0
Molybdenum	0.1	0.04	0
Nitrate/nitrite (MCL)[b]	0.004	0.003	0
Selenium IV	0	0	0
Selenium VI	9E-03	6E-03	0
Thallium	0.2	0.1	0
Codisposed CCW and Coal Refuse – 41 landfills			
Cancer			
Arsenic III	2E-05	6E-06	0
Arsenic V	6E-06	7E-10	0

(continued)

50th Percentile Risk Results by CCW Type: Landfills, Groundwater-to-Drinking-Water Pathway (continued)

Chemical	50th Percentile HQ or Cancer Risk Value[a]		
	Unlined Units	Clay-Lined Units	Composite-Lined Units
Noncancer			
Aluminum	4E-06	2E-09	0
Antimony	0.05	0.02	0
Barium	5E-05	7E-07	0
Boron	8E-03	3E-03	0
Cadmium	0.02	4E-03	0
Cobalt	2E-05	0	0
Lead (MCL)[b]	0.01	2E-07	0
Molybdenum	0.02	6E-03	0
Nitrate/nitrite (MCL)[b]	0.04	0.009	0
Selenium IV	2E-09	2E-15	0
Selenium VI	0.03	0.01	0
Thallium	0.2	0.07	0

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.
[b] Values are ratios of exposure concentration to MCL.

Table 4-3. 90th Percentile Risk Results by CCW Type: Surface Impoundments, Groundwater-to-Drinking-Water Pathway

Chemical	90th Percentile HQ or Cancer Risk Value[a]		
	Unlined Units	Clay-Lined Units	Composite-Lined Units
Conventional CCW – 44 surface impoundments			
Cancer			
Arsenic III	2E-03	9E-04	2E-07
Arsenic V	7E-04	2E-04	0
Noncancer			
Aluminum	2E-03	1E-03	2E-07
Barium	5E-03	3E-03	2E-11
Boron	7	4	5E-03
Cadmium	0.5	0.3	4E-11
Cobalt	0.9	0.4	0
Lead (MCL)[b]	3	0.7	1E-21
Molybdenum	8	5	7E-03
Nitrate/nitrite (MCL)[b]	20	10	9E-04
Selenium IV	0.4	0.1	1E-04

(continued)

90th Percentile Risk Results by CCW Type: Surface Impoundments, Groundwater-to-Drinking-Water Pathway (continued)			
Chemical	**90th Percentile HQ or Cancer Risk Value[a]**		
	Unlined Units	**Clay-Lined Units**	**Composite-Lined Units**
Selenium VI	2	1	1E-03
Codisposed CCW and Coal Refuse – 72 surface impoundments			
Cancer			
Arsenic III	2E-02	7E-03	4E-06
Arsenic V	2E-02	2E-03	3E-09
Noncancer			
Aluminum	0.3	0.07	6E-07
Barium	7E-03	3E-03	9E-07
Boron	1	0.5	2E-03
Cadmium	9	3	5E-05
Cobalt	500	200	3E-06
Lead (MCL)[b]	9	1	1E-19
Molybdenum	3	2	4E-03
Nitrate/nitrite (MCL)[b]	0.4	0.2	1E-04
Selenium IV	0.3	0.1	3E-10
Selenium VI	0.8	0.4	1E-03

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.

[b] Values are ratios of exposure concentration to MCL.

Table 4-4. 50th Percentile Risk Results by CCW Type: Surface Impoundments, Groundwater-to-Drinking-Water Pathway

Chemical	**50th Percentile HQ or Cancer Risk Value[a]**		
	Unlined Units	**Clay-Lined Units**	**Composite–Lined Units**
Conventional CCW – 44 surface impoundments			
Cancer			
Arsenic III	1E-04	6E-05	0
Arsenic V	2E-05	4E-06	0
Noncancer			
Aluminum	2E-05	1E-05	8E-20
Barium	1E-04	1E-04	0
Boron	0.4	0.2	3E-11
Cadmium	0.05	0.02	0
Cobalt	0.2	0.05	0

(continued)

50th Percentile Risk Results by CCW Type: Surface Impoundments, Groundwater-to-Drinking-Water Pathway (continued)

Chemical	50th Percentile HQ or Cancer Risk Value[a]		
	Unlined Units	Clay-Lined Units	Composite–Lined Units
Lead (MCL)[b]	0.05	0.007	0
Molybdenum	1	0.5	2E-11
Nitrate/nitrite (MCL)[b]	0.1	0.05	7E-08
Selenium IV	8E-04	4E-10	0
Selenium VI	0.1	0.07	2E-11
Codisposed CCW and Coal Refuse – 72 surface impoundments			
Cancer			
Arsenic III	6E-04	2E-04	0
Arsenic V	3E-04	4E-05	0
Noncancer			
Aluminum	5E-04	4E-05	0
Barium	4E-04	2E-04	0
Boron	0.1	0.06	5E-15
Cadmium	0.1	0.05	0
Cobalt	20	6	0
Lead (MCL)[b]	0.1	0.01	0
Molybdenum	0.8	0.3	3E-18
Nitrate/nitrite (MCL)[b]	0.03	0.01	4E-08
Selenium IV	3E-03	9E-05	0
Selenium VI	0.1	0.03	5E-15

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.

[b] Values are ratios of exposure concentration to MCL.

4.1.1.2 FBC Wastes

Tables 4-5 and **4-6** show the 90th and 50th percentile risk results for FBC landfills by liner type. These results suggest lower risks than for conventional CCW and CCW codisposed with coal refuse. The difference may be attributed to lower FBC leachate concentrations and the alkaline nature of FBC waste. Note that clay-lined FBC landfills show higher risks than unlined facilities, which is counterintuitive considering how clay-lined and unlined units are designed and operated. This result reflects the characteristics of the limited number and locations of FBC landfills.[5] When the risk results of an exposure pathway are viewed at a resolution finer than the analysis design, a small sample size, along with the interactions of liner type with other site-

[5] FBC WMU data were available for only seven landfills (3 unlined, 3 clay-lined, and 1 composite-lined), and it is not known how representative these data are with respect to WMU characteristics and locations throughout the United States.

based inputs, can produce unexpected results. In the case of FBC wastes, the characteristics of the three unlined landfills (primarily infiltration rate and areas) were such that their risks were lower than the three clay-lined FBC landfills.

Table 4-5. 90th Percentile Risk Results for FBC Wastes: Landfills, Groundwater-to-Drinking-Water Pathway

Chemical	90th Percentile HQ or Cancer Risk Value[a]		
	Unlined Units	Clay-Lined Units	Composite-Lined Units
FBC Waste – 7 landfills			
Cancer			
Arsenic III	3E-05	6E-05	0
Arsenic V	2E-05	2E-05	0
Noncancer			
Aluminum	4E-06	2E-05	0
Antimony	0.8	3	0
Barium	4E-04	2E-03	0
Boron	0.02	0.07	0
Cadmium	0.1	0.3	0
Cobalt	0.4	0.8	0
Lead (MCL)[b]	0.4	0.6	0
Molybdenum	0.2	0.5	0
Nitrate/nitrite (MCL)[b]	0.03	0.07	5E-08
Selenium IV	3E-14	0.05	0
Selenium VI	0.08	0.1	0
Thallium	1	4	0

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000-year period of the analysis.

[b] Values are ratios of exposure concentration to MCL.

Table 4-6. 50th Percentile Risk Results for FBC Wastes: Landfills, Groundwater-to-Drinking-Water Pathway

Chemical	50th Percentile HQ or Cancer Risk Value[a]		
	Unlined Units	Clay-Lined Units	Composite-Lined Units
FBC Waste – 7 landfills			
Cancer			
Arsenic III	0	4E-07	0
Arsenic V	0	5E-10	0
Noncancer			
Aluminum	0	0	0
Antimony	0	0.09	0

(continued)

50th Percentile Risk Results for FBC Wastes: Landfills, Groundwater-to-Drinking-Water Pathway (continued)

Chemical	50th Percentile HQ or Cancer Risk Value[a]		
	Unlined Units	Clay-Lined Units	Composite-Lined Units
Barium	0	0	0
Boron	0	0.003	0
Cadmium	0	0.01	0
Cobalt	0	3E-03	0
Lead (MCL)[b]	0	2E-04	0
Molybdenum	0	0.04	0
Nitrate/nitrite (MCL)[b]	3E-08	0.004	0
Selenium IV	0	5E-15	0
Selenium VI	0	0.01	0
Thallium	0	0.2	0

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000-year period of the analysis.
[b] Values are ratios of exposure concentration to MCL.

4.1.1.3 Comparing Landfills and Surface Impoundments

The full-scale analysis produced lower risks for landfills than for surface impoundments. The higher risks for surface impoundments as compared to landfills reflect higher constituent concentrations in the surface impoundment wastes and a higher hydraulic head in an impoundment that drives leachate into the underlying soil with greater force than infiltration in landfills. This higher head results in a greater flux of contaminants to groundwater during the active life of the surface impoundment, especially in unlined units. In combination with the higher CCW constituent concentrations in surface impoundment porewater and a greater proportion of unlined units, these factors lead to more and higher risk exceedances for surface impoundments than for landfills.

4.1.1.4 The Effect of Liners

The analysis demonstrates that the presence of liners, especially composite liners, reduce leaching and risks from CCW landfills and surface impoundments. Note that 90th percentile risks from composite liners are zero for most constituents for landfills, which means that in 90 percent of the cases, the contaminant did not reach the receptor well in the 10,000 year limit for this analysis. Composite liners also reduced risks for surface impoundments for several constituents at the 90th percentile by 4 to 10 orders of magnitude and generated risk results well below the cancer risk range or noncancer risk criterion used for this analysis. Infiltration rates for composite-lined surface impoundments are largely controlled by leak density (see **Section 3.5**), which is an empirical distribution from the same source as the landfill infiltration rates (U.S. EPA, 2002b), and are subject to similar uncertainties.

Zero values reflect the liner leakage rates in the empirical data set used to develop composite landfill liner infiltration rates used in this risk assessment (from U.S. EPA, 2002b; see **Section 3.4.2**), which are mostly zero values or very low in terms of infiltration rate. Although these infiltration rates are based on the best data available to EPA, these data are not specific to CCW facilities. This represents an uncertainty in the analysis (see **Sections 3.4.2** and **4.4.3.2**).

4.1.1.5 Modeled Peak Concentration Arrival Times

Arrival times for the peak well concentrations used to calculate groundwater to drinking water risks for selected CCW constituents (arsenic, boron, cobalt, selenium, and thallium) are plotted as cumulative distributions for surface impoundments and landfills in the figures in **Appendix L.** These constituents were selected to represent the chemicals with the highest risks and to span the range of mobility in the subsurface. **Table 4-7** summarizes these time of travel results by showing selected percentiles from these distributions for each WMU/liner combination modeled in the risk assessment.

As can be seen in Table 4-7, the peak arrival times for most constituents in unlined surface impoundment is less than 100 years (i.e., peak concentration occurs before or shortly after surface impoundment closure). The 10th percentile ranges from 70 years (for arsenic III, boron, and selenium VI) to 76 years (for selenium IV). The 50th percentile arrival times remain under 100 years for most constituents, with only the less mobile forms of arsenic and selenium having 50th percentile arrival times later than 100 years.

Arrival times for unlined landfills are much longer, ranging up to thousands of years. For boron and selenium IV, the 50th percentiles are 2,000 and 10,000 years respectively. However, even at the 10th percentile, arrival times ranged from 300 years (for boron) to 4,600 years (for selenium IV).

At the higher percentiles, arrival times shown as greater than 10,000 years indicate that the contaminant plume did not reach the well before the simulation ended. Although the plume might eventually reach the well in these cases, EPA does not believe that extending the simulation beyond 10,000 years would have captured any significant risk beyond what was captured by the selection of the 90th percentile values, which reflect cases where the plume did reach the well. In other words, the 90th percentile values would not be influenced by whether lower percentile concentrations were zero or the concentration at a peak beyond 10,000 years.

Table 4-7. Time to Peak Well Concentration by WMU and Liner Type as Modeled

Liner	Time to Peak (years)[a,b]							
	Percentile	Arsenic III	Arsenic IV	Boron	Cobalt	Selenium IV	Selenium VI	Thallium[c]
Landfills (all waste types)								
Unlined	10	400	2,000	300	1,200	4,600	400	580
	30	1,100	7,100	880	4,100	9,400	1,000	1,100
	50	2,800	9,700	2,000	7,800	10,000	2,600	2,300
	70	6,400	10,000	4,300	10,000	>10,000	5,500	4,400
	90	>10,000	>10,000	9,400	>10,000	>10,000	10,000	9,700

(continued)

Time to Peak Well Concentration by WMU and Liner Type as Modeled (continued)

Liner	Time to Peak (years)[a,b]							
	Percentile	Arsenic III	Arsenic IV	Boron	Cobalt	Selenium IV	Selenium VI	Thallium[c]
Compacted clay	10	400	1,900	550	1,400	8,100	400	570
	30	1,400	8,200	1,400	5,900	>10,000	1,300	1,200
	50	4,000	10,000	5,600	10,000	>10,000	5,100	4,300
	70	>10,000	>10,000	10,000	>10,000	>10,000	10,000	10,000
	90	>10,000	>10,000	>10,000	>10,000	>10,000	>10,000	>10,000
Synthetic or composite (clay and synthetic)	10	10,000	>10,000	9,600	>10,000	10,000	9,000	>10,000
	30	>10,000	>10,000	>10,000	>10,000	>10,000	>10,000	>10,000
	50	>10,000	>10,000	>10,000	>10,000	>10,000	>10,000	>10,000
	70	>10,000	>10,000	>10,000	>10,000	>10,000	>10,000	>10,000
	90	>10,000	>10,000	>10,000	>10,000	>10,000	>10,000	>10,000
Surface Impoundments (all waste types)								
Unlined	10	70	73	70	71	76	70	N/A
	30	73	97	72	78	610	72	N/A
	50	78	220	74	97	4,400	74	N/A
	70	91	890	80	190	10,000	80	N/A
	90	170	6,500	110	970	>10,000	110	N/A
Compacted clay	10	75	95	75	86	81	75	N/A
	30	86	350	80	140	3,000	80	N/A
	50	110	1,300	90	270	7,900	90	N/A
	70	150	5,000	110	690	10,000	110	N/A
	90	340	10,000	150	3,100	>10,000	150	N/A
Synthetic or composite (clay and synthetic)	10	1,300	10,000	960	9,500	1,900	990	N/A
	30	3,900	>10,000	2,800	>10,000	6,900	2,800	N/A
	50	8,600	>10,000	4,400	>10,000	>10,000	4,600	N/A
	70	>10,000	>10,000	7,000	>10,000	>10,000	7,300	N/A
	90	>10,000	>10,000	10,000	>10,000	>10,000	10,000	N/A

[a] Arrival times have been rounded to two significant digits.
[b] >10,000 indicates that the contaminant plume did not reach the receptor well during the modeled period.
[c] N/A = Not Applicable. Thallium was not modeled for surface impoundments (see **Section 4.1.1** above).

As with the higher constituent concentrations that are characteristic of surface impoundments, the shorter arrival times for surface impoundments are primarily due to the hydraulic head of the waste liquids in the unit; by contrast, landfill leaching is driven solely by infiltration of precipitation through the cap and liner of the unit and the peak concentration takes much longer to reach the well.

The arrival times presented in Table 4-7 correspond to the arrival of the maximum estimated risks for each model run. However, for model runs where the risk range or HQ criterion was exceeded, the first exceedence would sometimes occur earlier than the maximum risk arrivals reported in Table 4-7. This is consistent with the appearance of damage cases described in U.S. EPA (2007), which were sometimes observed sooner than the time-to-peak estimates in Table 4-7.

4.1.2 Groundwater-to-Surface-Water (Fish Consumption) Pathway

Like the drinking water results above, the fish consumption results are organized by waste type so that different waste chemistries could be accounted for. **Section 4.1.2.1** presents the results for conventional CCW and codisposed CCW by WMU and liner type. FBC wastes were also modeled for the surface water pathway, and these results are treated separately in **Section 4.1.2.2**. Note that only the four constituents that failed the surface water screen were probabilistically modeled for this scenario. Of those, thallium risks are not presented for surface impoundments because of a high proportion (>90%) of nondetects in the surface impoundment data (see **Section 4.4.3.1** for further discussion). The screening analysis results in **Section 3.2.4** and **Table 3-6** show which CCW constituents exceeded the surface water screening criteria.

4.1.2.1 Conventional CCW and CCW Codisposed with Coal Refuse

Tables 4-8 and **4-9** present the 90th and 50th percentile risk results, respectively, by waste type and liner type for CCW landfills for the fish consumption pathway. The results presented are for a fisher's child because those risks were consistently higher than the risks for the adult fisher. As seen in these tables, the results for landfills that codispose of CCW are not drastically different from those that handle only conventional CCW. At the 90th percentile, only unlined landfills that comanage CCW present risks at an HQ of 1 (for selenium). The remainder of the modeled constituents had risks below an excess cancer risk of 1 in 100,000 or an HQ of 1 at the 90th percentile. 50th percentile results were all well below these levels for both cancer and noncancer risks.

Tables 4-10 and **4-11** present the 90th and 50th percentile risk results, respectively, by waste type and liner for CCW surface impoundments for the fish consumption pathway. Again, risks are higher for surface impoundments than for landfills because of the higher waste concentrations and the higher hydraulic head in these units, as discussed previously for the drinking water pathway. Results at that 90th percentile exceeded an HQ of 1 for selenium in unlined (HQ of 3) and clay-lined (HQ of 2) impoundments managing conventional CCW, and also exhibited excess cancer risks just above 1 in 100,000 for arsenic in unlined (3 in 100,000) and clay-lined (2 in 100,000) impoundments comanaging CCW. Fish consumption pathway 50th percentile results are well below an excess cancer risk of 1 in 1,000,000 and an HQ of 1 for all constituents, waste management scenarios, and liner types.

Table 4-8. 90th Percentile Risk Results by CCW Type: Landfills, Groundwater-to-Surface-Water Pathway

Chemical[b]	90th Percentile HQ or Cancer Risk Value[a]		
	Unlined Units	Clay-Lined Units	Composite-Lined Units
Conventional CCW – 79 landfills			
Cancer			
Arsenic III	1E-06	1E-07	0
Arsenic V	4E-07	3E-09	0

(continued)

90th Percentile Risk Results by CCW Type: Landfills, Groundwater-to-Surface-Water Pathway (continued)

Chemical[b]	90th Percentile HQ or Cancer Risk Value[a]		
	Unlined Units	Clay-Lined Units	Composite-Lined Units
Noncancer			
Cadmium	0.09	6E-03	0
Selenium IV	6E-05	1E-04	0
Selenium VI	0.3	0.04	0
Thallium	0.4	0.04	0
Codisposed CCW and Coal Refuse – 41 landfills			
Cancer			
Arsenic III	2E-06	8E-07	0
Arsenic V	2E-06	2E-07	0
Noncancer			
Cadmium	0.05	0.01	0
Selenium IV	0.03	9E-03	0
Selenium VI	1	0.4	0
Thallium	0.4	0.2	0

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.

[b] Note that only the chemicals with adequate data that were identified in the screening analysis as needing further assessment (see **Section 3.2.4**) were modeled.

Table 4-9. 50th Percentile Risk Results by CCW Type: Landfills, Groundwater-to-Surface-Water Pathway

Chemical[b]	50th Percentile HQ or Cancer Risk Value[a]		
	Unlined Units	Clay-Lined Units	Composite-Lined Units
Conventional CCW – 79 landfills			
Cancer			
Arsenic III	3E-10	7E-11	0
Arsenic V	4E-14	1E-18	0
Noncancer			
Cadmium	2E-05	3E-06	0
Selenium IV	0	0	0
Selenium VI	2E-04	4E-05	0
Thallium	1E-04	5E-05	0

(continued)

50th Percentile Risk Results by CCW Type: Landfills, Groundwater-to-Surface-Water Pathway (continued)

Chemical[b]	50th Percentile HQ or Cancer Risk Value[a]		
	Unlined Units	Clay-Lined Units	Composite-Lined Units
Codisposed CCW and Coal Refuse – 41 landfills			
Cancer			
Arsenic III	4E-09	3E-09	0
Arsenic V	2E-10	8E-14	0
Noncancer			
Cadmium	1E-04	6E-05	0
Selenium IV	6E-10	1E-15	0
Selenium VI	3E-03	3E-03	0
Thallium	1E-03	1E-03	0

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.

[b] Note that only the chemicals with adequate data that were identified in the screening analysis as needing further assessment (see **Section 3.2.4**) were modeled.

Table 4-10. 90th Percentile Risk Results by CCW Type: Surface Impoundments, Groundwater-to-Surface-Water Pathway

Chemical[b]	90th Percentile HQ or Cancer Risk Value[a]		
	Unlined Units	Clay-Lined Units	Composite-Lined Units
Conventional CCW – 44 surface impoundments			
Cancer			
Arsenic III	8E-06	4E-06	1E-12
Arsenic V	2E-06	4E-07	0
Noncancer			
Cadmium	0.09	0.04	2E-15
Selenium IV	0.6	0.04	1E-07
Selenium VI	3	2	2E-06
Codisposed CCW and Coal Refuse – 72 surface impoundments			
Cancer			
Arsenic III	3E-05	2E-05	1E-14
Arsenic V	2E-05	8E-06	6E-19
Noncancer			
Cadmium	0.5	0.3	8E-13
Selenium IV	0.2	0.05	0

(continued)

90th Percentile Risk Results by CCW Type: Surface Impoundments, Groundwater-to-Surface-Water Pathway (continued)

Chemical[b]	90th Percentile HQ or Cancer Risk Value[a]		
	Unlined Units	Clay-Lined Units	Composite-Lined Units
Selenium VI	1	0.8	7E-10

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.

[b] Note that only the chemicals with adequate data that were identified in the screening analysis as needing further assessment (see **Section 3.2.4**) were modeled.

Table 4-11. 50th Percentile Risk Results by CCW Type: Surface Impoundments, Groundwater-to-Surface-Water Pathway

Chemical[b]	50th Percentile HQ or Cancer Risk Value[a]		
	Unlined Units	Clay-Lined Units	Composite–Lined Units
Conventional CCW – 44 surface impoundments			
Cancer			
Arsenic III	4E-08	6E-10	0
Arsenic V	7E-09	2E-11	0
Noncancer			
Cadmium	6E-04	6E-06	0
Selenium IV	5E-05	1E-11	0
Selenium VI	0.02	3E-04	0
Codisposed CCW and Coal Refuse – 72 surface impoundments			
Cancer			
Arsenic III	6E-08	1E-08	0
Arsenic V	3E-08	2E-09	0
Noncancer			
Cadmium	1E-03	2E-04	0
Selenium IV	8E-05	4E-07	0
Selenium VI	3E-03	8E-04	0

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.

[b] Note that only the chemicals with adequate data that were identified in the screening analysis as needing further assessment (see **Section 3.2.4**) were modeled.

As with the groundwater-to-drinking-water pathway analysis, the absence of risk from composite-lined units indicates that the liners modeled in this analysis are effective at preventing contaminants from reaching the surface waterbodies of interest. One should keep in mind that all surface water results are calculated assuming that constituents are being added to the waterbodies only via groundwater. However, for surface impoundment operation, effluent is constantly being discharged directly into that same waterbody. These discharges are regulated

under the Clean Water Act, and although they pose an uncertainty in the analysis, they are outside the scope of the risk assessment (see **Section 4.4.1** for further discussion).

4.1.2.2 FBC Wastes

Tables 4-12 and **4-13** show the 90th and 50th percentile risk results for FBC landfills by liner type. These results are much lower than those for conventional CCW and comanaged CCW landfills seen above, and suggest that releases from FBC landfills do not present a hazard to surface waters. This difference may be attributed to lower FBC leachate concentrations and the alkaline nature of FBC wastes. However, as with the FBC results reported for drinking water, the results here are strongly influenced by the small sample size of site data available. Thus, the limitation of only having seven sites may present an uncertainty in the analysis.

Table 4-12. 90th Percentile Risk Results for FBC Wastes: Landfills, Groundwater-to-Surface-Water Pathway

Chemical	90th Percentile HQ or Cancer Risk Value[a]		
	Unlined Units	Clay-Lined Units	Composite-Lined Units
FBC Waste – 7 landfills			
Cancer			
Arsenic III	4E-12	7E-08	0
Arsenic V	3E-12	3E-08	0
Noncancer			
Cadmium	7E-07	0.02	0
Selenium IV	3E-17	8E-03	0
Selenium VI	5E-06	0.1	0
Thallium	5E-06	0.2	0

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.

[b] Note that only the chemicals with adequate data that were identified in the screening analysis as needing further assessment (see Section 3.2.4) were modeled.

Table 4-13. 50th Percentile Risk Results for FBC Wastes: Landfills, Groundwater-to-Surface-Water Pathway

Chemical	50th Percentile HQ or Cancer Risk Value[a]		
	Unlined Units	Clay-Lined Units	Composite-Lined Units
FBC Waste – 7 landfills			
Cancer			
Arsenic III	0	3E-13	0
Arsenic V	0	6E-14	0

(continued)

50th Percentile Risk Results for FBC Wastes: Landfills, Groundwater-to-Surface-Water Pathway (continued)

Chemical	50th Percentile HQ or Cancer Risk Value[a]		
	Unlined Units	Clay-Lined Units	Composite-Lined Units
Noncancer			
Cadmium	0	2E-05	0
Selenium IV	0	8E-16	0
Selenium VI	0	1E-03	0
Thallium	0	1E-03	0

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.

[b] Note that only the chemicals with adequate data that were identified in the screening analysis as needing further assessment (see Section 3.2.4) were modeled.

4.1.3 Results by Liner Type

The effect of liner type on human health risk for the groundwater-to-drinking-water pathways can be seen in Tables 4-1 through 4-6 and for the groundwater-to-surface water pathway in Tables 4-8 through 4-13, which present risks for WMUs that are unlined, clay lined, and lined with composite liners from the 1995 EPRI survey data (EPRI, 1997). At the 90th percentile, lined units produced lower risk estimates than unlined units for all constituents modeled. Composite liners produced very low to zero risk estimates as compared to clay liners for all constituents modeled for both landfills and surface impoundments. For surface impoundments, clay liners produced higher risk estimates for all constituents as compared to clay liners in landfills. Similar trends are evident at the 50th percentile, where composite liners produced risk estimates of zero or near zero for all constituents for surface impoundments.

Table 4-14 shows how frequent each of the liner types is in the 1995 EPRI survey data modeled in this analysis, and it compares these data with the liner type frequency in the more recent DOE/EPA study (U.S. DOE, 2006). The 56 WMUs surveyed in the U.S. DOE 2006 study were commissioned between 1994 and 2004. Although the actual number of WMUs that were established in that timeframe cannot be verified, based on proxy data (i.e., CCW available for disposal in those states with identified, new WMUs and coal-fired power plant generating capacity), the sample coverage is estimated to be at least 61–63 percent of the total population of the newly commissioned WMUs.[6] With the exception of one landfill, the newly constructed facilities are all lined, with either clay, synthetic, or composite liners. The single unlined landfill identified in the recent DOE report receives bottom ash, which is characterized as an inert waste by the state, and therefore, a liner is not required.

[6] For additional details as to how these estimates were derived, the reader is referred to the DOE study, pages S-2 – S-3 of the Summary Section and Section 3.1.2..

Table 4-14. Liner Types in EPRI Survey

Liner Type	Landfills	Surface Impoundments
1995 EPRI Survey[a] – 181 facilities		
Unlined	40%	68%
Compacted clay	45%	27%
Synthetic or composite (clay and synthetic)	16%	5%
Total	100%	100%
2004 DOE Survey[b] – 56 Facilities		
Unlined	3%	0%
Compacted clay	29%	17%
Synthetic or composite (clay and synthetic)	68%	83%
Total	100%	100%

[a] EPRI (1997)
[b] U.S.DOE (2006)

As Table 4-14 shows, there is a marked trend away from unlined WMUs in favor of lined units, with a distinct preference for synthetic or composite liners. Comparison of the 26 coal combustion plants in both the EPRI survey and the DOE/EPA survey (U.S. DOE, 2006) shows that although most of those facilities (17 of 26) were using unlined WMUs in 1995, all 26 are now placing wastes in new or expanded landfills or surface impoundments that are lined with clay, synthetic, or composite liners. However, it is likely that the older unlined units were closed with wastes in place, and that these wastes could therefore still pose a threat through groundwater pathways. Also, the number of unlined unit that continue to operate in the United States cannot be determined from the available data.

As described in **Sections 3.4.1** and **3.5.1**, the characteristics of the liners used in the CCW risk were taken from the IWEM model as representative of the general performance of each liner type. For landfills, an engineered compacted clay liner (3 feet thick, with a hydraulic conductivity of 1×10^{-7} cm/s) reduced the 90th percentile risk by a factor of about 2 to 4 compared to no liner, but did not change the constituents at or above an excess cancer risk of 1 in 100,000 (arsenic, excess cancer risk of 1 in 5,000) or an HQ of 1 (thallium, HQ of 2). For surface impoundments, clay liners did reduce the risk to just below an HQ of 1 for cobalt, lead, and selenium.

Composite (clay and synthetic) liners, as modeled in this risk assessment (see **Sections 3.4** and **3.5**), were much more effective at reducing risk for all constituents; 90th (and 50th) percentile risks with composite liners for landfills were zero[7] for arsenic and metals and very low or zero for reactive nitrogen compounds (nitrate and nitrite), and were well below an excess cancer risk of 1 in 100,000 or an HQ of 1 for all constituents for surface impoundments. The analysis used data collected for composite liner performance at industrial waste management

[7] The absence of risk indicates that contaminant infiltration rates were too small for the contaminant plume to reach the receptor well during the 10,000 year period of the analysis. See Section 3.2.2 for a discussion of the empirical liner infiltration data used in this analysis.

facilities, including liner leakage rate for landfills and the number of liner perforations for surface impoundments (TetraTech, 2001). Because data on CCW liner leakage rates were not available, there is some uncertainty in applying these Industrial D Guidance liner performance data to CCW disposal units. Still, these rates do reflect actual performance data from liners under real WMUs. They demonstrate that composite liners can be effective in reducing leaching from CCW WMUs and suggest that there will be a decrease in risk from CCW disposal if more facilities line their WMUs with composite or clay liners. Information from the more recent DOE/EPA study (U.S. DOE, 2006) indicates that composite liners are becoming more prevalent in newly constructed facilities, so the risks from CCW disposal should be lower for newer CCW landfills and surface impoundments.

4.1.4 Constituents Not Modeled in the Full-Scale Assessment

As described in **Section 3.2.4**, full-scale modeling was not conducted for all 21 constituents that were above the screening criteria in the initial screening analysis; only constituents that were judged likely to have generally higher risks to human health and ecological health were modeled in the full-scale risk assessment.[8] Five chemicals (chromium, fluoride, manganese, vanadium, and nickel) had drinking water pathway HQs in the screening analysis ranging from 1 to less than 6 for surface impoundments, and three (chromium, fluoride, and vanadium) had screening HQs of 2 for landfills.

To address these unmodeled constituents, EPA developed surrogate risk attenuation factors by dividing the screening risk results by the full-scale risk results, across all unit (liner) types combined, for the constituents modeled in the full-scale assessment. This comparison was done only for the drinking water exposure pathway, the only human health exposure pathway for which the risks for these constituents were above the screening criteria. **Table 4-15** shows the risk attenuation factor statistics for the modeled constituents, and **Table 4-16** shows the results of applying the median and 10th percentile attenuation factors to the screening risk results for the marginal constituents. Differences in attenuation among the modeled constituents reflect differences in contaminant sorption and mobility. To be conservative, the 10th percentile attenuation factor was selected as a high-end value representing the more mobile constituents, such as arsenic, selenium, and molybdenum. The 50th percentile (or median) risk represents a central tendency value.

Table 4-15. Risk Attenuation Factor[a] Statistics for Modeled Constituents—Groundwater to Drinking Water Pathway

Statistic	Landfill	Surface Impoundment
10th percentile	7	1.6
50th percentile	12	2.6
Average	16	3.3
Maximum	40	9.3

(continued)

[8] These constituents of concern had human health HQs greater than 6 or both ecological HQs greater than 100 at the 90th percentile.

**Risk Attenuation Factor[a] Statistics for Modeled Constituents—
Groundwater to Drinking Water Pathway (continued)**

Statistic	Landfill	Surface Impoundment
Number of data points	9	8

[a] The risk attenuation factor is the ratio of the full-scale analysis risk and screening analysis risk for a constituent modeled in the full-scale analysis.

Table 4-16. Summary of Risk Screening Values for Unmodeled Constituents Using Risk Attenuation Factors—Groundwater-to-Drinking-Water Pathway

WMU/Pathway	Landfill			Surface Impoundment		
	Screening HQ	HQ with Median Attenuation	HQ with 10th Percentile Attenuation	Screening HQ	HQ with Median Attenuation	HQ with 10th Percentile Attenuation
Chromium VI	2.3	0.2	0.3	4.2	1.6	2.6
Fluoride	1.8	0.2	0.3	5.2	2.0	3.3
Manganese	1	0.1	0.1	5.6	2.2	3.5
Vanadium	2.2	0.2	0.3	2.3	0.9	1.4
Nickel	-	-	-	1.3	0.5	0.8

For landfills, the risk attenuation factors ranged from 6 to 40, with the lower attenuation factors mainly representing the more mobile constituents (i.e., those with lower soil sorption potential). Both the median and 10th percentile risk attenuation factors were adequate to reduce risks for all nine constituents below an HQ of 1.

For surface impoundments, risk attenuation factors were considerably lower, ranging from 1 to 9, reflecting higher contaminant mobility due to the higher hydraulic head in surface impoundments (as compared to landfills) and a lower proportion of liners. For the same reason, the screening HQs for surface impoundments were higher than the landfill HQs. As a result of this combination of higher HQs and lower risk attenuation factors, only the HQ for nickel was reduced to below 1 by applying the attenuation factors. The other constituents (chromium, fluoride, manganese, and vanadium) still show risks slightly above an HQ of 1, with HQs ranging from 1.4 to 3.5 at 10th percentile attenuation. This is consistent with the general trend in this analysis of surface impoundments showing higher risks than CCW landfills.

4.1.5 Human Health (Groundwater and Fish Consumption) Damage Case Review

Table 4-17 summarizes the proven damage cases from U.S. EPA (2007) that showed an impact on groundwater, usually through an exceedence of an MCL or state groundwater standard for one or more metals. As detailed in U.S. EPA (2007), these facilities represent worst-case disposal conditions: all are unlined, several represent fills in old quarries, and many have wastes disposed of below the water table. Groundwater standard exceedences are usually onsite or closely offsite. As one can see in the table, the same metals showing risk exceedences for unlined facilities (arsenic, boron, cadmium, lead, molybdenum, and selenium) in this analysis were reported as exceedences in the groundwater damage cases. Other incidents of groundwater

contamination supporting the conclusions of this risk assessment can be found in the published literature in references such as Lang and Schlictmann (2004) and Zilmer and Fauble (2004).

Table 4-18 summarizes the five proven damage cases from U.S. EPA (2007) that showed a fish consumption advisory for selenium. Although these were all cases where CCW surface impoundments directly discharged to a lake, and hence larger fluxes of surface impoundment waters into the waterbody of interest than through the groundwater-to-surface-water pathway, they do support the finding of this risk assessment that the fish consumption pathway is of potential concern for selenium in CCW.

Table 4-17. Summary of Proven Damage Cases with Groundwater Impacts (U.S. EPA, 2007)

Proven NODA Damage Case[a]	Reported Groundwater Impacts
1. Salem Acres Site, MA (lagoons and fly ash pile)	Minor – As, Cr, Pb
2. City of Beverly/ Vitale Brothers Fly Ash Pit, MA (quarry fill)	Al, As, Fe, Mn, Se over MCLs
3. Don Frame Trucking, Inc. Fly Ash Landfill, NY	Pb, Mn over MCLs
4. Virginia Electric Power Co. (VEPCO) Possum Point, VA (ash ponds)	Cd, Ni over MCLs
5. PEPCO Morgantown Generating Station Faulkner Off-site Disposal Facility, MD (landfills and settling ponds)	Low pH, iron staining
6. Virginia Power Yorktown Power Station Chisman Creek Disposal Site, VA (quarry fill)	Se, sulfate over MCL; green staining; As, Be, Cr, Cu, Mo, Ni, V over background
9. DOE Oak Ridge Y-12 Plant Chestnut Ridge Operable Unit 2, TN (ash pond)	Al, As, Fe, Pb, Mn over MCL
10. South Carolina Electric & Gas Canadys Plant, SC (ash ponds)	As above MCL outside compliance boundary; NI above state standard
13. Dairyland Power Cooperative E.J. Stoneman Generating Station Ash Disposal Pond, WI	Cd, Cr, sulfate, Mn, Fe, and Zn over MCLs onsite; B over background offsite
14. WEPCO Highway 59 Landfill, WI	As, Se, sulfate, B, Mn, Cl-, Fe over state standards
15. Alliant Nelson Dewey Ash Disposal Facility, WI	As, Se, sulfate, B, F- over state standards
16. WEPCO Cedar-Sauk Landfill, WI	Se, sulfate over MCLs; B over state standard
17. WEPCO Port Washington Facility, WI (quarry fill)	B over state standard; elevated Se
18. Lansing Board of Water & Light North Lansing Landfill, MI (quarry fill)	Li, Mn, Se above state standards
19. Northern Indiana Public Service Corp. Yard 520 Landfill Site, IN	As, B, Mn,, Mo, Pb contaminated residential wells
23. Basin Electric Power Cooperative W.J. Neal Station Surface Impoundment, ND	Al, As, Cd, Cr, Zn above MCL
24. Cooperative Power Association/United Power Coal Creek Station Surface Impoundments, ND	As, Se, sulfate, Cl above MCL; elevated B

[a] Numbers represent original case numbers in U.S. EPA (2007)

Table 4-18. Summary of Proven Damage Cases with Fish Consumption Advisories (U.S. EPA, 2007)

Proven NODA Damage Case	Reported Fish Consumption Advisory
7. Hyco Lake, Roxboro, North Carolina (surface impoundment discharge)	Selenium fish consumption advisory
11. Belews Lake, NC (surface impoundment discharge)	Selenium fish consumption advisory
20. Brandy Branch Reservoir, Texas (ash pond discharge)	Selenium fish consumption advisory
21. Southwestern Electric Power Company Welsh Reservoir, TX (ash pond discharge)	Selenium fish consumption advisory
22. Texas Utilities Electric Martin Lake Reservoir, TX (ash pond discharge)	Selenium fish consumption advisory; elevated selenium in birds

EPA has also found that CCW contaminants of concern in the damage cases agree with those exceeding a 1 in 100,000 excess cancer risk or an HQ of 1 in this analysis, building confidence that the risk assessment captures national conditions. **Table 4-19** compares the results from the 2007 draft risk assessment with the damage cases reported in the *Coal Combustion Waste Damage Case Assessments* (U.S. EPA, 2007) for the groundwater pathway.

Table 4-19. Modeled 90th and 50th Percentile Risk Results vs. Reported Groundwater Exceedences

Constituent	2007 Risk Assessment[a]		Damage Cases[b]			Consistent Results as of 2007[f]
	90th %ile	50th %ile	Human Health Effects[c]	Cosmetic/ Aesthetic Effects[d]	State Standard[e]	
Aluminum	–	–	–	✓	–	Yes
Antimony	✓	–	–	–	–	No
Arsenic	✓	T	✓	–	✓	Yes
Barium	–	–	–	–	–	Yes
Beryllium	Screened		–	–	–	Yes
Boron	✓	–	✓	–	✓	Yes
Cadmium	✓	–	✓	–	–	Yes
Chloride	Not Screened		–	✓	✓	N/A
Chromium	RAF		✓	–	–	Uncertain
Cobalt	✓	T	–	–	–	No
Copper	Screened		–	–	–	Yes
Fluoride	RAF		–	–	✓	Uncertain
Iron	Not Screened		–	✓	✓	N/A
Lead	✓	–	✓	–	–	Yes
Lithium	Not Screened		–	–	✓	N/A
Manganese	RAF		✓	✓	✓	Uncertain
Molybdenum	✓	–	✓	–	–	Yes
Nickel	RAF		✓	–	✓	Uncertain
Nitrate/Nitrite	✓	–	–	–	–	No
Selenium	✓	–	✓	–	✓	Yes
Silver	Screened		–	–	–	Yes
Sulfate	Not Screened		–	✓	✓	N/A
Thallium	✓	–	–	–	–	No
Vanadium	RAF		–	–	–	Uncertain

(continued)

Modeled 90th and 50th Percentile Risk Results vs. Reported Groundwater Exceedences (continued)

Constituent	2007 Risk Assessment[a]		Damage Cases[b]			Consistent Results as of 2007[f]
	90th %ile	50th %ile	Human Health Effects[c]	Cosmetic/ Aesthetic Effects[d]	State Standard[e]	
Zinc	Screened		–	✓	–	Yes

[a] Not Screened = Constituent was not considered due to lack of health-based benchmarks.
Screened = Constituent showed no risk potential in the screening assessment.
RAF = Constituent showed risk potential in the screening assessment, and was analyzed with risk attenuation factors.
✓ = Constituent underwent full probabilistic modeling and was shown to pose a risk to human health in the landfill scenario, the surface impoundment scenario, or both.
– = Constituent underwent full probabilistic modeling and was not shown to pose a risk to human health

[b] ✓ = At least one proven damage case showed an exceedence of this constituent.
– = No proven damage cases have yet shown an exceedence of this constituent.

c ✓ = Exceedences of primary maximum contaminant levels (MCLs) or other health-based numbers published by EPA.

[d] ✓ = Exceedences of secondary MCLs, which would not result in harm to human health.

e ✓ = Exceedences of a relevant state standard.

f Yes = Results of risk assessment and damage cases either both indicated a risk to human health or both indicated no risk to human health.
No = The risk assessment indicated risks where none have yet been found in a proven damage case.
Uncertain = It is possible that the results were consistent, but due to lack of probabilistic modeling, no definitive conclusion can be made.
N/A = Constituent was not examined at any stage in the 2007 risk assessment, so it was not possible to draw any conclusions as to consistency.

The first category of constituents is those for which the risk assessment and the damage cases agree, either because both the risk assessment results and the damage cases indicated risks, or because both the risk assessment results and damage cases did not indicate risks. The former group had model results exceeding the cancer risk range or an HQ of 1, and also appeared in the damage cases with exceedances of maximum contaminant levels (MCLs), state groundwater standards, or other health-based numbers (arsenic, boron, cadmium, lead, molybdenum, and selenium). The latter group did not show the potential for risks above an HQ of 1 from the risk assessment and did not appear in the damage case literature (aluminum, barium, beryllium, copper, silver, and zinc).

The second category of constituents is those for which the risk assessment and the damage cases did not agree. Four modeled constituents (antimony, cobalt, thallium, and nitrate/nitrite) showed risk at the 90th percentile but no damage cases had been proven as of 2007. This could indicate that (1) the risk assessment was conservative for these constituents, (2) not enough time has passed to see the remaining constituents appear in damage cases, (3) corrective action was taken when the first constituent(s) was observed, so further constituents that would have appeared at the same site were never seen, or (4) these constituents are not tested for as frequently as the constituents found in the proven damage cases.

The third category of constituents is those that were not screened out, and were analyzed using risk attenuation factors (chromium, fluoride, manganese, nickel, and vanadium). Because all that is known is that these constituents have the potential to pose a risk to human health, they cannot currently be compared to the damage case results.

The final category of constituents is those that were not evaluated at either the screening or modeling stages because no health-based values were available for comparison. These four constituents (chlorine, iron, lithium, and sulfate) appeared in damage cases because of exceedences of aesthetic or state levels, not because of a known risk to human health.

Table 4-20 compares the results from the 2007 draft risk assessment with the damage cases reported in U.S. EPA (2007) for the fish consumption pathway. The only fish consumption advisories documented in CCW damage cases are for selenium. This is consistent with the risk assessment for selenium. The two constituents that do not pose a risk in the risk assessment (cadmium and thallium) were also not part of any fish consumption advisories in the damage cases. The one inconsistency is arsenic, for which the risk assessment shows a cancer risk of 1 in 50,000, slightly exceeding an excess cancer risk of 1 in 100,000. However, no arsenic fish consumption advisories exist at proven damage case sites. This inconsistency could indicate that (1) the risk assessment was conservative with respect to arsenic, (2) not enough time has passed to see arsenic appear in fish advisories at these sites, or (3) the arsenic exceedences have not been detected in random fish tissue samples thus far.

Table 4-20. Modeled 90th and 50th Percentile Risk Results vs. Reported Fish Consumption Exceedences

Constituent	2007 Risk Assessment[a]		Damage Cases[b]	Consistent Results as of 2007[c]
	90th %ile	50th %ile		
Arsenic	✓	–	–	No
Cadmium	–	–	–	Yes
Selenium	✓	–	✓	Yes
Thallium	–	–	–	Yes

[a] ✓ = Constituent underwent full probabilistic modeling and was shown to pose a risk to human health in the landfill scenario, the surface impoundment scenario, or both.
– = Constituent underwent full probabilistic modeling and was not shown to pose a risk to human health

[b] ✓ = At least one proven damage case showed a fish consumption advisory for this constituent.
– = No proven damage cases have yet shown a fish consumption advisory for this constituent.

[c] Yes = Results of risk assessment and damage cases either both indicated a risk to human health or both indicated no risk to human health.
No = The risk assessment indicated risks where none have yet been found in a proven damage case.

4.2 Ecological Risks

EPA defines ecological risk characterization in terms of (1) the risk estimation, which integrates the exposure and stressor-response profile to estimate the likelihood of adverse ecological effects and (2) the risk description, which synthesizes the overall conclusion of the assessment and addresses assumptions, uncertainty, and limitations.

For assessments that are based on a HQ approach, as this one was, the comparison of modeled exposure concentrations to CSCLs to estimate risk has a binary outcome: either the constituent concentration is above the concentration corresponding to an HQ of 1 or the concentration is less than or equal to the concentration corresponding to an HQ of 1. For the full-scale analysis, an ecological HQ greater than 1 was selected by EPA as a criterion for decision making. Because the CSCLs were based on *de minimis* ecological effects, it is generally presumed that an HQ at or below 1 indicates a low potential for adverse ecological effects for those receptors included in the analysis for which data are available. However, it is important to recognize that although this method provides important insight into the potential for adverse ecological effects, the results are relevant only to those receptors that were included in the assessment and for which data were available. The results have limited utility in interpreting the ecological significance of predicted effects, and caution should be exercised in extrapolating to ecosystems (e.g., wetlands) and receptors (e.g., threatened and endangered species) not explicitly modeled.

This section presents risk results for direct surface impoundment exposure (as evaluated in the 1998 CCW risk assessment, U.S. EPA, 1998a,b), screening results for boron that indicate risks to plants from aboveground exposure, and the two groundwater-to-surface-water ecological exposure pathways investigated in the full-scale analysis: (1) receptors exposed to CCW constituents in the water column (surface water receptors) and (2) receptors exposed to CCW constituents in bed sediment (sediment receptors). Results are presented for the two WMU types addressed in the analysis: landfills and surface impoundments, and are broken out separately for the different unit (liner) types. Finally, ecological damage case reports from U.S. EPA (2007) and from the published literature are summarized as field evidence supporting the conclusions of this risk assessment.

The ecological risk results and damage cases suggest the potential for adverse ecological effects to plants, terrestrial organisms, and aquatic systems from CCW releases into the subsurface and subsequent connection with surface waters, particularly for CCW managed in unlined surface impoundments. As with human health risks, the higher prevalence of liners in newer facilities should result in lower risks in current and future CCW disposal facilities than those presented in this risk assessment.

4.2.1 Direct Surface Impoundment Exposure

The current risk assessment addresses exposure to receptors in offsite surface waterbodies impacted by groundwater, where both the aquatic communities and upper trophic level terrestrial receptors would need to be protected.[7] The 2003 CCW constituent database used

[7] The 2002 CCW constituent database does not include impoundment water samples, and the direct exposure pathway was not addressed.

in this analysis does not include impoundment water samples, and the direct exposure pathway could not be addressed for ecological risk. However, the CCW risk assessment conducted in 1998 (U.S. EPA, 1998a,b) did consider direct exposure of ecological receptors to surface impoundment waters. The approach in the 1998 study restricted the analysis to terrestrial receptors that obtain food and prey from the surface impoundments and excluded aquatic receptors living in the water column because surface impoundments are not intended to be a habitat for aquatic species. For the terrestrial and aquatic receptors considered, the 1998 analysis used the same CSCLs and a similar methodology to that used in the CCW screening analysis (e.g., comparison of 90th percentile waste concentrations with CSCLs).

The 1998 direct exposure results are provided in **Figure 4-1** and show HQs greater than 100 for boron, selenium, lead, barium, and cadmium. This, along with the damage case results presented in **Section 4.2.4**, show a clear likelihood of risks to terrestrial organisms that obtain food and prey from CCW surface impoundments. It is probable that ecological receptors eat and drink from CCW surface impoundments in some settings. In addition, ecological receptors, particularly amphibians who may lay their eggs in surface impoundments, are probably exposed through chronic contact with wastewater. Because amphibians are prey to a large variety of animals (e.g., raptors; wading birds; mammalian omnivores, such as foxes, raccoons, and weasels), this exposure is transferred up the food chain. Aquatic plants, although not often a focus of this ecological risk assessment, are directly exposed in surface impoundments. Plants, in turn, may be ingested by vertebrates and invertebrates at higher trophic levels.

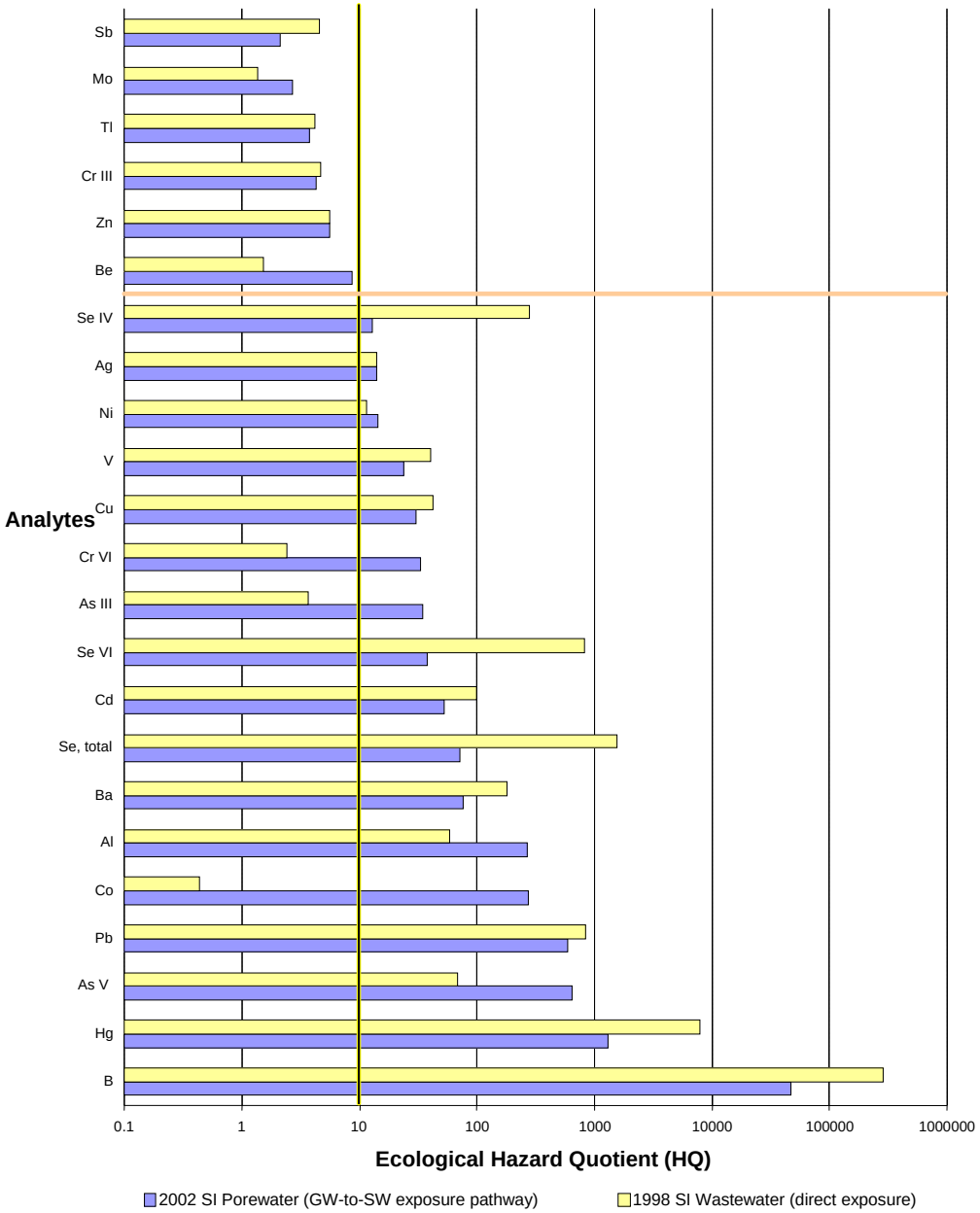


Figure 4-1. CCW surface impoundment ecological screening risks: Direct exposure to surface impoundment wastewater.

4.2.2 Surface Water Receptors (Full-Scale Analysis)

Tables 4-21 and **4-22** present the 90th and 50th percentile results from the full-scale ecological risk assessment of the groundwater-to-surface-water pathway for surface water receptors for CCW landfills and surface impoundments. For landfills, boron (HQ of 281) , lead (HQ of 8), selenium (HQ of 2), arsenic (HQ of 2), and barium (HQ of 2) show risks above an HQ of 1 at the 90th percentile for the unlined units. Clay liners reduce the risks below an HQ of 1 for all constituents except for boron, which still has a very high HQ (78 for the clay liner versus 281 for unlined). For surface impoundments, all modeled constituents except cadmium

and aluminum showed 90th percentile risks above the ecological risk criterion, with boron showing an HQ over 2,000 for the unlined units, and other HQs ranging from 3 to 22 for unlined units. The 50th percentile results are all well below an HQ of 1 for landfills and only exceed an HQ of 1 for boron in unlined surface impoundments (HQ = 7).

As with other pathways and receptors, the difference in the number and magnitude of ecological HQs that exceed the risk criterion between landfills and surface impoundments is likely the result of (1) higher CCW constituent concentrations in surface impoundment porewater and (2) the greater flux of contaminants to groundwater predicted during the active life of the surface impoundment. As discussed in **Section 4.1**, the higher infiltration rates for surface impoundments result from a higher hydraulic head in the impoundment and a higher proportion of unlined surface impoundments than landfills in the 1995 EPRI survey data used for this risk assessment.

Table 4-21. Summary of 90th Percentile Full-Scale CCW Ecological Risk Results: Groundwater-to-Surface-Water Pathway, Aquatic Receptors[a]

Chemical	90th Percentile Ecological HQ			Exposure Pathway	Receptor
	Unlined Units	Clay-Lined Units	Composite-Lined Units		
Landfills					
Boron	281	78	0.07	direct contact	aquatic biota
Lead	8	0.4	2E-06	ingestion	river otter
Selenium (VI)	2	0.7	3E-04	direct contact	aquatic biota
Arsenic (V)	2	0.1	4E-08	direct contact	aquatic biota
Barium	2	0.2	0	direct contact	aquatic biota
Cadmium	0.5	0.1	3E-05	direct contact	aquatic biota
Aluminum	0.01	0.003	1E-07	direct contact	aquatic biota
Surface Impoundments					
Boron	2,375	854	257	direct contact	aquatic biota
Lead	22	7	2	ingestion	river otter
Arsenic (V)	13	4	5	direct contact	aquatic biota
Selenium (VI)	12	4	1	direct contact	aquatic biota
Cobalt	6	3	5	direct contact	aquatic biota
Barium	3	1	0.8	direct contact	aquatic biota
Cadmium	1	0.7	0.4	direct contact	aquatic biota
Aluminum	0.03	0.01	0.008	direct contact	aquatic biota

[a] Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.

Table 4-22. Summary of 50th Percentile Full-Scale CCW Ecological Risk Results: Groundwater-to-Surface-Water Pathway, Aquatic Receptors[a]

Chemical	50th Percentile Ecological HQ			Exposure Pathway	Receptor
	Unlined Units	Clay-Lined Units	Composite-Lined Units		
Landfills					
Boron	0.2	0.1	0	direct contact	aquatic biota
Lead	7E-05	4E-08	0	ingestion	river otter
Selenium (VI)	0.002	0.001	0	direct contact	aquatic biota
Arsenic (V)	4E-06	5E-09	0	direct contact	aquatic biota
Barium	1E-10	4E-12	0	direct contact	aquatic biota
Cadmium	2E-04	9E-05	0	direct contact	aquatic biota
Aluminum	3E-07	8E-09	0	direct contact	aquatic biota
Surface Impoundments					
Boron	7	0.4	5E-05	direct contact	aquatic biota
Lead	0.05	0.0008	0	ingestion	river otter
Arsenic (V)	0.03	0.0007	0	direct contact	aquatic biota
Selenium (VI)	0.03	0.002	4E-07	direct contact	aquatic biota
Cobalt	0.01	0.001	0	direct contact	aquatic biota
Barium	0.006	0.0004	0	direct contact	aquatic biota
Cadmium	0.008	0.0003	0	direct contact	aquatic biota
Aluminum	0.0007	4E-05	4E-11	direct contact	aquatic biota

[a] Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.

4.2.3 Sediment Receptors (Full-Scale Analysis)

Tables 4-23 and 4-24 present the 90th and 50th percentile results of the ground-water-to-surface-water pathway for sediment receptors for landfills and surface impoundments. For unlined landfills, lead (HQ of 58), arsenic (HQ of 11), cadmium (HQ of 5), and antimony (HQ of 2) show 90th percentile risks above the ecological risk criterion. For clay lined landfills, only arsenic (HQ of 3) has an ecological HQ greater than 1. For surface impoundments, lead, arsenic, and cadmium showed 90th percentile HQs above 1 for unlined, clay-lined, and composite-lined units (with HQs ranging from 2 to 311). Although cadmium was not above the risk criterion in surface water, it did have an HQ of 30 in sediments at the 90th percentile for unlined surface impoundments and HQs of 9 and 2 for clay- and composite-lined impoundments respectively. None of the constituents modeled showed sediment risks at or above an HQ of 1 at the 50th percentile.

Table 4-23. Summary of 90th Percentile Full-Scale CCW Ecological Risk Results: Groundwater-to-Surface-Water Pathway, Sediment Receptors[a]

Chemical	90th Percentile Ecological HQ			Exposure Pathway	Receptor
	Unlined Units	Clay-Lined Units	Composite-Lined Units		
Landfills					
Lead	58	1	1E-06	direct contact	aquatic biota
Arsenic (III)	11	3	5E-04	ingestion	river otter
Cadmium	5	1	6E-05	direct contact	aquatic biota
Antimony	2	0.5	7E-05	direct contact	aquatic biota
Molybdenum	0.1	0.03	2E-05	direct contact	aquatic biota
Barium	0.006	6e-04	0	direct contact	aquatic biota
Surface Impoundments					
Lead	311	58	4	direct contact	aquatic biota
Arsenic (III)	127	55	31	ingestion	river otter
Cadmium	30	9	2	direct contact	aquatic biota
Molybdenum	0.9	0.3	0.1	direct contact	aquatic biota
Barium	0.008	0.004	0.002	direct contact	aquatic biota

[a] Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.

Table 4-24. Summary of 50th Percentile Full-Scale CCW Ecological Risk Results: Groundwater-to-Surface-Water Pathway, Sediment Receptors[a]

Chemical	50th Percentile Ecological HQ			Exposure Pathway	Receptor
	Unlined Units	Clay-Lined Units	Composite-Lined Units		
Landfills					
Lead	6E-05	9E-08	0	ingestion	spotted sandpiper
Arsenic (III)	4E-03	0.002	0	ingestion	spotted sandpiper
Cadmium	5E-04	2E-04	0	direct contact	sediment biota
Antimony	3E-04	1E-04	0	direct contact	sediment biota
Molybdenum	5E-05	3E-05	0	ingestion	spotted sandpiper
Barium	3E-13	8E-15	0	ingestion	spotted sandpiper
Surface Impoundments					
Lead	0.1	0.001	0	ingestion	spotted sandpiper
Arsenic (III)	0.4	0.02	4E-09	ingestion	spotted sandpiper
Cadmium	0.02	0.0007	0	direct contact	sediment biota
Molybdenum	0.004	0.0002	2E-08	ingestion	spotted sandpiper
Barium	1E-05	1E-06	0	ingestion	spotted sandpiper

[a] Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.

4.2.4 Constituents Not Modeled in the Full-Scale Assessment

As described in **Section 3.2.4**, full-scale modeling was not conducted for 6 constituents with generally lower risks to ecological receptors.[9] These chemicals (chromium, vanadium, beryllium, copper, silver, and zinc), had surface water pathway HQs in the screening analysis ranging from 16 to 110 for landfills, and four (chromium, vanadium, copper, and silver) had screening HQs ranging from 14 to 33 for surface impoundments.

These constituents were addressed using risk attenuation factors developed by dividing the screening risk results by the full-scale risk results for the constituents that were modeled in the full-scale assessment. **Tables 4-25** and **4-26** show the results of this comparison for the surface water ecological risk exposure pathway. Table 4-23 shows the risk attenuation factors for the modeled constituents, and Table 4-24 shows the results of applying the median (central tendency) and 10th percentile (conservative) attenuation factors to the screening risk results for constituents that were not modeled.

For landfills, the risk attenuation factors ranged from 50 to 2,000. Both the median and 10th percentile risk attenuation factors were adequate to reduce risks to an HQ below 1 for all constituents except for silver. Although silver shows an HQ of 1.5 using the 10th percentile attenuation factor, silver's low mobility would probably result in a higher attenuation factor (i.e., at the median or greater).

For surface impoundments, risk attenuation factors ranged from 7.1 to 64, reflecting higher contaminant mobility from the higher hydraulic head in the surface impoundments and a lower prevalence of liners (compared to landfills) in the 1995 EPRI data. HQs were reduced below 1 for all four unmodeled constituents with the median attenuation factor (38), and the HQ for silver was reduced to 0.8 by applying the 10th percentile attenuation factor (17). The other three constituents (chromium, vanadium, and copper) show HQs slightly above 1 with the10th percentile attenuation (HQs ranging from 1.4 to 1.9). Note that the risks for chromium are based on the protective assumption of 100 percent hexavalent chromium in CCW.

Table 4-25. Risk Attenuation Factor[a] Statistics for Modeled Constituents—Ecological Risk, Surface Water Pathway (all unit types combined)

Statistic	Landfill	Surface Impoundment
10th percentile	75	17
50th percentile	178	38
Average	483	38
Maximum	2,000	64
Number of data points	6	7

[a] The risk attenuation factor is the ratio of the full-scale analysis risk and screening analysis risk for a constituent modeled in the full-scale analysis.

[9] These constituents had only one or no ecological HQs greater than 100.

Table 4-26. Summary of Risk Screening Values for Unmodeled Constituents Using Risk Attenuation Factors—Ecological Risk, Surface Water Pathway

WMU/Pathway	Landfill			Surface Impoundment		
	Screening HQ	HQ with Median Attenuation	HQ with 10th Percentile Attenuation	Screening HQ	HQ with Median Attenuation	HQ with 10th Percentile Attenuation
Chromium VI	18	0.1	0.2	33	0.9	1.9
Vanadium	23	0.1	0.3	24	0.6	1.4
Beryllium	24	0.1	0.3	-	-	-
Copper	16	0.09	0.2	31	0.8	1.8
Silver	110	0.6	1.5	14	0.4	0.8
Zinc	16	0.09	0.2	-	-	-

4.2.5 Ecological Damage Cases

Cases of damages to terrestrial and aquatic organisms from improperly managed CCW are common in the literature. For example, Carlson and Adriano (1993) summarize such damage incidents, including those resulting from alkaline CCW effluent discharge to surface waterbodies and boron toxicity to plants. Rowe et al. (2002) provide a more comprehensive review, assessment, and meta-analysis of the ecotoxicity of CCW, focusing on aquatic disposal (i.e., CCW surface impoundments) and tabulating damages from over 20 years of field and laboratory studies in the published literature. Selenium and arsenic are most commonly associated with CCW damages to terrestrial and aquatic organisms. Cadmium, boron, chromium, and lead are also associated with CCW ecological risk. Hopkins et al. (2006) show deformities and reproductive effects in amphibians living on or near CCW disposal sites in Georgia, which are mainly attributed to selenium exposure.

Table 4-27 summarizes the proven CCW ecological damage cases from U.S. EPA (2007). Most of these cases are from surface impoundments and direct discharge into lakes and other water bodies. Along with the published results discussed in **Section 4.1.5**, these cases clearly support selenium and arsenic in coal ash as risks to aquatic ecosystems, as well as the adverse impacts of coal ash on terrestrial vegetation.

Table 4-27. Summary of Proven Damage Cases with Ecological Impacts (U.S. EPA, 2007)

Proven NODA Damage Case	Reported Ecological Impacts
2. City of Beverly/ Vitale Brothers Fly Ash Pit, MA (quarry fill)	Contamination of wetlands and surface waters
5. PEPCO Morgantown Generating Station Faulkner Off-site Disposal Facility, MD (landfills and settling ponds)	Vegetative damages, contamination of stream and wetland by GW
6. Virginia Power Yorktown Power Station Chisman Creek Disposal Site, VA (quarry fill)	As, Be, Cr, Cu, Mo, Ni, Se, V contamination of onsite ponds and offsite creek
7. Hyco Lake, Roxboro, North Carolina (surface impoundment discharge)	Se fish advisory; fish reproduction and population effects
8. Georgia Power Company, Plant Bowen, Cartersville, GA (ash pond over sinkhole)	Ash slurry release damaged creek
9. DOE Oak Ridge Y-12 Plant Chestnut Ridge Operable Unit 2, TN (ash pond)	Se, As, Tl elevated in bass; As over screening criteria; deformed fish; stress on aquatic ecosystem; Se plant and mammal uptake
11. Belews Lake, NC (surface impoundment discharge)	Fish advisory for Se; 16 of 20 fish species eliminated from lake
12. U.S. Department of Energy Savannah River Project, SC (landfill)	Impacts on amphibians (deformities) and snake (metabolic effects)
16. WEPCO Cedar-Sauk Landfill, WI	Wetland vegetative damage from B in groundwater
20. Brandy Branch Reservoir, Texas (ash pond discharge)	Se fish consumption advisory
21. Southwestern Electric Power Company Welsh Reservoir, TX (ash pond discharge)	Se fish consumption advisory
22. Texas Utilities Electric Martin Lake Reservoir, TX (ash pond discharge)	Se fish consumption advisory; elevated Se in birds

4.3 Sensitivity Analysis

EPA conducted a sensitivity analysis (U.S. EPA, 2009b) on the probabilistic risk assessment to determine which model inputs were most important to risk, which in turn helped focus additional analyses and data collection efforts on the most important drivers of risk, and helped identify the important factors to consider when evaluating regulatory and management options for CCW. The sensitivity analysis also helped identify parameters that are both sensitive and highly uncertain, which affects the confidence in the results.

The CCW sensitivity analysis used a response-surface regression method that derives a statistical model for risk (as the dependent variable) based on the input parameters from the probabilistic analysis (as independent variables). Environmental concentration (rather than risk) was chosen as the dependent variable for the sensitivity analysis because (1) there is a direct, linear relationship between environmental concentrations and risks and (2) the additional inputs used to calculate risk from environmental concentration (i.e., exposure factors, such as body weight, ingestion rates) are lifestyle variables that are not amenable to regulation to reduce or manage risk. Furthermore, these variables have well-established, peer-reviewed, national

distributions, which are regularly used in the probabilistic national risk analyses conducted by EPA. Therefore, the contribution of the exposure factors to the variability in risk was not particularly useful for the primary purposes of the sensitivity analysis, to better understand sources of uncertainty in the CCW risk results and to help focus regulatory development on sensitive variables that can be addressed through the RCRA regulatory process.

The outputs from the sensitivity analysis were goodness-of-fit values for the regression models and the relative importance of each input parameter in determining environmental concentrations across different WMU, waste type, and constituent scenarios. The goodness-of-fit values of the regression models were moderate to very good for the drinking water pathway (R^2=0.53–0.90) and good to very good for fish consumption (R^2=0.76–0.90). In general, the drinking water pathway had more input parameters that were significant (seven) than the fish consumption pathway (three). The most sensitive parameters for most (over 70 percent) of the drinking water scenarios[10] evaluated were parameters impacting groundwater flow:

- Infiltration rate within the WMU footprint
- Leachate concentration from the WMU
- Aquifer hydraulic conductivity and groundwater gradient (i.e., groundwater velocity).

For many (over 30 percent) of the scenarios, including those corresponding to strongly sorbing contaminants (i.e., metals with high soil/water partition coefficients), sorption and travel time parameters are also important, including

- Adsorption isotherm coefficient
- Depth to groundwater
- Receptor well distance.

For the fish consumption pathway, only three variables were consistently significant across scenarios:

- Infiltration rate within the WMU footprint
- Leachate concentration from the WMU
- Waterbody flow rate.

Additional detail on how the CCW sensitivity analysis was conducted can be found in U.S. EPA (2009b). In terms of the model inputs, the sensitivity analysis found that the most consistent drivers of the risk results were constituent concentration in waste leachate (i.e., the source term for the risk assessment and infiltration rate through the WMU), which is largely controlled by the liner conditions and, to a lesser extent, soil type and (for landfills only) precipitation. These variables and their uncertainties are discussed in the following section.

[10] Scenarios represent unique combinations of WMU, waste type, chemical, exposure pathway, and receptor.

4.4 Variability and Uncertainty

Variability and uncertainty are different conceptually in their relevance to a probabilistic risk assessment. Variability represents true heterogeneity in characteristics, such as body weight differences within a population or differences in pollutant levels in the environment. It accounts for the distribution of risk within the exposed population. Although variability may be known with great certainty (e.g., age distribution of a population may be known and represented by the mean age and its standard deviation), it cannot be eliminated and needs to be treated explicitly in the assessment. Uncertainty is a description of the imperfection in knowledge of the true value of a particular parameter. In contrast to variability, uncertainty can be reduced through additional information-gathering or analysis (i.e., better data, better models). EPA typically classifies the major areas of uncertainty in risk assessments as scenario uncertainty, model uncertainty, and parameter uncertainty. Scenario uncertainty refers to missing or incomplete information needed to fully define exposure and dose. Model uncertainty is a measure of how well the model simulates reality. Parameter uncertainty is the lack of knowledge regarding the true value of a parameter used in the assessment.

Variability arises from true heterogeneity in characteristics, such as body weight differences within a population or differences in contaminant levels in the environment.

Uncertainty represents a lack of knowledge about factors such as the nature of adverse effects from exposure to constituents, which may be reduced with additional research to improve data or models.

Uncertainty and variability can be addressed two ways:

- By varying parameter values in a probabilistic assessment such as a Monte Carlo analysis
- By comparing the data or results to other data or other studies such as damage cases or alternative results based on different assumptions.

In planning this assessment, EPA addressed as much of the variability as possible, either directly in the Monte Carlo analysis or through aggregation of the data into discrete elements of the analysis. For example, spatial variability in soil, aquifer, and climate data was accounted for by using distributions for soil and aquifer properties around the facility when the actual environmental characteristics around a WMU are uncertain. Conversely, variability in waste leachate concentrations was represented by a national database of CCW constituent concentrations from disposal sites around the country. These data were aggregated by waste and WMU types that were defined by statistically significant differences in concentration. Variability in human exposure factors (e.g., body weight, ingestion rates) was accounted for using national distributions that represent the range of possible values.

Because CCW is generated nationwide, its disposal may occur anywhere in the United States. Thus, this assessment characterized environmental conditions that influence the fate and transport of constituents in the environment using site-specific data collected around coal-fired power plants with onsite CCW disposal facilities. Spatial variability in environmental setting was accounted for by the site-to-site variables for the 181 CCW disposal sites modeled in the

analysis using 41 different climate regions and 9 different hydrologic regions throughout the contiguous 48 states.

In summary, a distribution of exposures was developed that included specific consideration of the variability in the following sensitive model parameters

- WMU characteristics, in particular liner type (which strongly influences infiltration rate)
- CCW constituent concentrations in waste leachate
- Distance to nearest well
- Site-specific environmental conditions (especially groundwater flow conditions)
- Human exposure factors.

Uncertainty was also considered in the analysis by using reasonable ranges and distributions when variables were not known exactly. For example, when a soil texture or groundwater flow conditions could not be precisely assigned at a site, multiple soil types or hydrogeologic environments were sampled based on the soil and aquifer types that were likely to be present at the site.

The treatment of variability and uncertainty in model parameters using a Monte Carlo simulation formed the basis for the national exposure distributions used in this analysis to estimate risk. Previous sections of this document describe how EPA generated distributions and estimated input parameter values and then used these values in models to estimate risk. The discussion in this section focuses on how this treatment of variability and uncertainty affects the analysis results and on various comparisons we performed on the results or critical input data to evaluate uncertainty. **Table 4-28** lists the more important uncertainties described in this section, along with whether the uncertainty is likely to underestimate or overestimate risk, or if its effect on the risk results is uncertain.

Table 4-28. Summary of CCW Uncertainties and Their Effect on Risk Estimates

Uncertainty	Likely Effect on Risk		
	Overestimates	Uncertain	Underestimates
Scenario Uncertainties			
CCW Management Unit Data (1995 EPRI Survey)		✓	
Liner type (as built, 1995; liners more prevalent today)	✓		
Direct discharge from CCW impoundments (not addressed in CCW risk assessment; covered by NPDES)			✓
Effect of the 10,000-year timeframe for groundwater (complete leaching, long timeframe)	✓		
Receptor populations evaluated (high-end receptor and child living near CCW WMU)	✓		
Additive risks across pathways (not considered)			✓
Co-occurrence of ecological receptors and constituents	✓		
Ecosystems and receptors at risk		✓	

(continued)

Summary of CCW Uncertainties and Their Effect on Risk Estimates (continued)

Uncertainty	Likely Effect on Risk		
	Overestimates	Uncertain	Underestimates
Model Uncertainties			
Clean closure of surface impoundments			✓
Arsenic and selenium speciation	✓		
100% bioavailability of constituents to ecological receptors	✓		
Compaction of landfilled waste	✓		
Landfills above water table			✓
Indirect ecological effects (not considered)			✓
Full mixing effects on aquifer pH (full mixing assumed; effect depends on constituent)	✓	✓	✓
Goethite versus hydrous ferric oxide sorbent	✓		
Multiple constituent exposures (not considered)			✓
Parameter Uncertainties			
Waste concentrations (2002 CCW constituent database)		✓	
Appropriateness of leachate data (TCLP results)		✓ (noncancer)	✓ (cancer)
Constituents with many nondetect analyses (e.g., mercury)		✓	
Treatment of nondetect analyses at half detection limit		✓	
WMU locations (1995 EPRI survey data)		✓	
WMU characteristics (1995 EPRI survey liner types, unit sizes)	✓		
Well location (MSW landfill survey data)		✓	
Well location (well always within plume)	✓		
Location and characteristics of waterbodies		✓	
Soil and aquifer characteristics		✓	
Waterbodies intercepting the groundwater plume	✓		
Human exposure factors		✓	
All drinking water from CCW-contaminated well)	✓		
Human health benchmarks	✓ (cancer)	✓ (noncancer)	
Ecological benchmarks		✓	

4.4.1 Scenario Uncertainty

Sources of scenario uncertainty include the assumptions and modeling decisions that are made to represent an exposure scenario. Because this risk assessment attempted to characterize current conditions by estimating risks from actual CCW disposal sites across the country, it was subject to less scenario uncertainty than risk assessments that rely on hypothetical conceptual models. However, certain aspects of the scenario are uncertain.

CCW Management Unit Data. The landfills and surface impoundments modeled in this risk assessment were placed, sized, and lined according to data from the 1995 EPRI survey (EPRI, 1997). New data collected by EPA and DOE since this risk assessment was conducted (U.S. DOE, 2006) indicate that liners are much more prevalent in WMUs constructed or expanded from 1994 through 2004 than in units in place before that. This suggests that the risks

may be lower for future CCW disposal facilities (although most of the unlined WMUs have been closed with wastes remaining in the units).

Liner-related questions are especially important because liner configurations greatly influence infiltration rates, one of the most sensitive parameters in the risk assessment. In terms of risks through groundwater pathways, this risk assessment has shown that liners, in particular composite (combined clay and synthetic) liners, can limit risks through subsurface exposure pathway, and the DOE/EPA survey shows that liners are more prevalent in newly constructed WMUs and WMU expansions. Although the DOE/EPA survey does not shed light on how many unlined facilities are still operating today, it does indicate that more units are lined today than were in the 1995 EPRI survey data set on which this risk assessment was based.

Although it would have been possible to address this uncertainty by evaluating different hypothetical liner scenarios for each facility, such an approach was outside the original scope of this risk assessment, which was to evaluate current CCW management activities, not hypothetical management scenarios. Furthermore, this approach likely would not have changed the general conclusion of the risk assessment that composite lined landfills pose less risk than clay lined landfills and that unlined landfills pose the greatest risk.

Direct Discharge of CCW Impoundments into Surface Water. Because this risk assessment addressed CCW disposal under RCRA, it did not include risks from the direct discharge of wastes into waterbodies, which are regulated under the Clean Water Act. Although not relevant for the management of RCRA waste disposal, EPA recognizes that CCW surface impoundment effluent may pose additional risks.

Effect of the 10,000-Year Timeframe for Groundwater. The risk assessment assumed that contaminant concentrations in the leachate remain constant throughout the 10,000-year modeling timeframe, although leaching may or may not persist for 10,000 years, depending on model inputs. The waste concentration model input was assumed to be a portion of the total waste concentration available to be leached, and it was assumed that 100% of the constituent in the waste could leach from the landfill. The nonlinear fate and transport solution used for metallic constituents in the unsaturated zone module of EPACMTP is based on the assumption that the leachate concentration released from the waste management unit is constant over time (see Section 3.3.5.3 of U.S. EPA, 2003b). Although a leaching profile that changes over time might be more realistic, the simplified leaching profile used by the model does not lead to a poorer estimate of risk associated with groundwater exposures. The adoption of a simplified leaching profile to support a non-linear sorption approach in the unsaturated zone offered a greater benefit and defensibility to the overall approach than assuming linear partitioning and a depleting leachate profile would have.

Receptor Populations Evaluated. The human receptors evaluated for the CCW risk analysis were a family with children residing near the CCW disposal facility, drinking from a private well screened in a surficial aquifer or eating fish caught from a nearby stream or lake impacted by CCW leachate. Additionally, except for a 15-day vacation, it was assumed that adults and children were exposed daily and that the private well was the only source of drinking water. Although it is possible for other types of individuals to be exposed, the use of the resident adult and child as protective of other receptors and pathways is a high-end, simplifying

assumption of the analysis. The lack of information to define and model actual exposure conditions also introduces uncertainty into this assessment, but EPA believes that the national distribution of exposure factors used is appropriate for a national assessment.

In addition, not all possible exposure pathways were evaluated. For example, the risk assessment did not consider potential indirect exposure to humans through game species that may have been exposed to surface impoundment waste (e.g., deer drinking surface impoundment water). This represents a potential uncertainty in the analysis.

Additive Risks Across Pathways. The human receptors evaluated in the CCW risk assessment were assumed not to consume both contaminated fish and drinking water from the same waterbody because untreated surface water is not considered potable water (municipal water treatment facilities were assumed to reduce contaminant levels prior to consumption). EPA also did not consider the potential cumulative exposure from contaminated fish and groundwater in the CCW risk assessment, because the exposures are likely to occur over different timeframes (because of differences in transit time of the contaminant plume to wells versus surface waterbodies) and may involve different receptors (because a resident near a CCW surface impoundment or landfill and exposed via groundwater may not be a recreational fisher). Although this could potentially miss some higher exposures for a maximally exposed individual, analysis of the individual pathway results does not indicate that adding such risks would change the conclusions of this risk assessment in terms of the constituents exceeding the risk criteria. Also, risks were high enough for single chemicals for human exposure pathways (notably arsenic) that this would not change the basic conclusion of the risk assessment that there are potentially significant risks to human health from CCW disposal in landfills and surface impoundments.

Co-Occurrence of Ecological Receptors and Constituents. As a simplification for national-scale analyses in the absence of site-based data, co-occurrence of the ecological receptors and the constituents of concern is typically assumed. However, the prior probability that a receptor will be found in waterbodies affected by constituent releases from CCW WMUs is not known, nor is it known whether a receptor will forage for food in contaminated areas or if those areas do, in fact, support the type of habitat needed by the receptor. Although the assumption of co-occurrence was necessary for this analysis, relatively few field studies are available to demonstrate the relationship between adverse ecological effects and constituent releases from CCW as it is currently managed.

Ecosystems and Receptors at Risk. One challenge in conducting a predictive ecological risk assessment intended to reflect risks at a national scale is representing *all* of the receptors and ecosystems at risk. In *Wastes from the Combustion of Coal by Electric Utility Power Plants - Report to Congress* (U.S. EPA, 1988b), the authors pointed out that plants or animals of concern were located within a 5-km radius of the CCW WMUs at 12 to 32 percent of the sites. Although these figures are of limited spatial resolution, they suggest the possibility that threatened and endangered species or critical habitats may be at risk from CCW constituents. Examples of other critical assessment endpoints not evaluated in this analysis include the following:

- **Managed Lands:** Because protected lands play a critical role in preserving plant and animal species, managed areas in the United States represent well-recognized ecological

values. Managed lands refer to a variety of lands designated by the federal government as worthy of protection, including National Wildlife Refuges, National Forests, Wilderness areas, and National Recreation areas.

- **Critical Habitats:** Although critical habitats may be defined in a number of ways (e.g., presence of threatened species, decreasing habitat area), wetlands are widely recognized as serving critical ecological functions (e.g., maintenance of water quality). The U.S. Fish and Wildlife Service estimates that approximately 45 percent of the Nation's threatened and endangered species directly depend on aquatic and wetland habitats. Consequently, impacts of chemical stressors on wetland habitats may have high ecological (and societal) significance. The presence of critical habitats such as wetlands is also used to inform the selection of ecological receptors (e.g., amphibians, waterfowl) and the construction of appropriate food webs.

- **Threatened and Endangered Species:** For most ecological risk assessments of chemical stressors, available data on toxicity and biological uptake are sufficient to support the evaluation of effects on representative species populations or generalized communities (e.g., the aquatic community). However, despite their obvious value, threatened and endangered species are frequently excluded from the analytical framework for national rulemakings. The assessment of threatened and endangered species requires a site-specific approach in which locations, habitats, and species of concern are identified and characterized with respect to the spatial scale of constituent releases.

Although these classes of receptors and potential ecological hazards are not explicitly considered in the analysis, conditions represented by simulations in the upper end of the risk distribution (higher risk scenarios) should reasonably characterize many situations with such sensitive species or habitats.

Impact on Groundwater as a Resource. The risk assessment did not explicitly consider potential impacts on the availability of groundwater in the future (e.g., contaminated groundwater becoming unsuitable for consumption), but the results do clearly indicate that there can be a reduction in resource availability if CCW is improperly disposed. However, the scope of the risk assessment was to evaluate human health and ecological effects associated with current waste disposal practices and conditions, and a quantitative evaluation of potential future reductions in groundwater availability as a consequence of CCW disposal practices was not conducted as part of this analysis.

4.4.2 Model Uncertainty

Model uncertainty is associated with all models used in a risk assessment because models and their mathematical expressions are simplifications of reality that are used to approximate real-world conditions and processes and their relationships. Computer models are simplifications of reality, requiring exclusion of some variables that influence predictions but that cannot be included in models either because of their complexity or because data are lacking on a particular parameter. Models do not include all parameters or equations necessary to express reality because of the inherent complexity of the natural environment and the lack of sufficient data to describe the natural environment. Because this was a probabilistic assessment that predicted

what may occur with the management of CCW under actual scenarios, it is possible to compare the results of these models to specific situations.

The risk assessor needs to consider the importance of excluded variables on a case-by-case basis, because a given variable may be important in some instances and not important in others. A similar problem can occur when a model that is applicable under one set of conditions is used for a different set of conditions. In addition, in some instances, choosing the correct model form is difficult when conflicting theories seem to explain a phenomenon equally well. In other instances, EPA does not have established model forms from which to choose to address certain phenomena, such as facilitated groundwater transport.

The models used in this analysis were selected based on science, policy, and professional judgment. These models were selected because they provide the information needed for this assessment and because they are generally considered to reflect the state of the science. Even though the models used in this analysis are used widely and have been accepted for numerous applications, they each retain significant sources of uncertainty. These limitations are well documented in the model development references cited in **Section 3**.

Although the sources of model uncertainty in this assessment could result in either an overestimation or an underestimation of risk, the models used in this assessment have been developed over many years to support regulatory applications. As a result, they have been designed to be protective of the impacted populations that they represent. In other words, where simplifying assumptions are necessary, the assumptions are made in a way that will not underestimate risk.

Assumption of Clean Closure of Surface Impoundments. As described in **Section 3.5.1**, the surface impoundment model treats a surface impoundment as a temporary waste management unit with a set operational life. At the end of this life, clean closure is assumed; all wastes are removed and there is no further release of waste constituents to groundwater. Although this simplifying assumption is not consistent with the practice to close CCW surface impoundments with wastes in place, and it limits the length of potential exposure, the peak annual leachate concentrations on which the CCW risk results were based are not likely to be affected. Releases to groundwater are much higher during surface impoundment operation because the higher hydraulic head in an operating impoundment drives wastewater into the underlying soil with greater force than infiltration through the impoundment cover after the impoundment is closed. This higher head results in a greater flux of contaminants to groundwater during the active life of the surface impoundment, especially in unlined units. Thus, even if the post-closure period were modeled, the corresponding results would not be as high as the peak annual leachate concentrations used in the analysis.

Arsenic and Selenium Speciation. Because the models used in this assessment do not speciate metals during soil or groundwater transport, arsenic and selenium speciation in the subsurface is a significant groundwater modeling uncertainty in this analysis. Arsenic can occur in either a +3 (arsenic III) or +5 (arsenic V) oxidation state in groundwater, with arsenic III being the more mobile form. Selenium can occur in either a +4 (selenium IV) or +6 (selenium VI) oxidation state in groundwater, with selenium VI being the more mobile form. Because the soil and groundwater models assume one form for each model run, the risk results presented for

arsenic and selenium were originally based on 100% arsenic III and selenium VI, which is a high-end assumption (i.e., arsenic III has higher risks than arsenic V and selenium VI has higher risks than selenium IV). Although arsenic is generally thought to occur in the +3 form in leachate, there is evidence from damage cases at CCW disposal sites that suggests that arsenic III is converted to arsenic V during subsurface transport at some sites (see, for example, U.S. EPA, 2000, 2003e; Lang and Schlictmann, 2004; Zillmer and Fauble, 2004). To address the uncertainty of running the model with 100% arsenic III and selenium VI, the models were also run assuming 100% arsenic V and selenium IV. The results from the two species should bracket the results expected given some mixing of oxidation states.

Bioavailability of Constituents to Ecological Receptors. For the purposes of this analysis, the model assumed that all forms of a constituent were equally bioavailable to ecological receptors, and therefore, the actual exposures that may occur in the field tend to be overestimated, thus making this a high-end assumption. Both the chemical form and the environmental conditions influence bioavailability and ultimately the expression of adverse effects. For example, as discussed above, the form of arsenic has been shown to profoundly influence mobility and toxicity.

Compaction of Landfilled Waste. The source model did not consider potential compaction of CCW waste over time. Such compaction could decrease the hydraulic conductivity and the associated water infiltration. However, no readily available data were identified to support an analysis of the influence of CCW compaction on infiltration rates. The current approach would tend to overestimate infiltration rates compared to a model that would adjust the hydraulic conductivity over time due to compaction. EPA believes this is an appropriately conservative assumption given the lack of the information needed to accurately model the effects of waste compaction.

Landfills Assumed to be Above Water Table. The landfill source model and EPACMTP assume that the source is above the water table. However, some actual CCW disposal units do extend below the water table. Because waste intersecting the saturated zone may increase groundwater concentrations, the approach may underestimate risk in some cases. However, including this effect would strengthen a general conclusion of the analysis that potentially unacceptable risks exist in some cases with unlined and clay lined CCW landfills.

Indirect Ecological Effects. Indirect ecological effects (e.g., depletion of food resources) were not considered in the analysis. For any given facility, the spatial scale of potential contamination would affect a very small proportion of the home range for typical species; determining impacts on food supply and habitat quality with regard to the landscape and overall health of the animals is not currently possible in a national-level assessment (and difficult to understand or estimate in the majority of site-specific assessments). In addition, many species are opportunistic feeders and will seek other areas if food sources decline, regardless of the source of the stress to the food supply. For these reasons, EPA does not believe that it is possible to consider indirect ecological effects in a national risk assessment like CCW.

Aquifer pH. As explained in **Section 3.4**, aquifer pH was used to select the metal sorption coefficients that were in turn used to calculate retardation coefficients for groundwater transport of the CCW constituents. To estimate pH in an aquifer impacted by CCW leachate, the

CCW risk analysis assumed that, after entering the aquifer, the leachate plume thoroughly mixes with the ambient, uncontaminated groundwater. However, because this mixing zone is largely at the periphery of the groundwater plume, thorough mixing may or may not occur at actual sites. The full mixing assumption results in higher receptor point concentrations for most metals, because metal sorption and precipitation tend to increase (i.e., Kd goes up) with higher pH and full mixing tends to reduce the pH of CCW leachate, which is normally alkaline (i.e., assuming full mixing results in a lower groundwater pH and lower sorption).

To assess the effect of this simplifying assumption on the risk results, we compared two landfill Monte Carlo simulations for coal ash waste containing As(III) and coal ash waste containing As(V): (1) the fully mixed aquifer assumption and (2) an assumption that no mixing occurs in the aquifer and the leachate pH is the governing pH for Kd selection. These two metal species were selected because their sorption isotherm behavior with pH change differs; Kds derived from As(III) isotherms tend to decrease as pH increases (which is typical of most metal species examined in the risk assessment), while Kds derived from As(V) isotherms tend to increase with increasing pH.

Percentiles of peak receptor well concentration from the As (III) and As (V) simulations were selected and compared by calculating the percent change with mixing assumption as follows:

$$\%\ Change = \frac{C_{\text{No Mix}} - C_{\text{Full Mix}}}{C_{\text{Full Mix}}} \times 100$$

where

$C_{\text{No Mix}}$ = Simulated peak receptor well concentration for a select percentile based on a no mixing assumption (mg/L)

$C_{\text{Full Mix}}$ = Simulated peak receptor well concentration for a select percentile based on a fully mixed assumption (mg/L)

Table 4-29 compares the percent change in peak receptor well As (III) and As (V) concentrations between the well mixed and no mixing scenarios over a range of peak well percentiles. The results indicate that As(V) has a sensitivity to pH that leads to increased receptor well concentrations under the no mixing assumption (i.e., when the leachate pH is used to determine Kd in the saturated zone) relative to the well-mixed assumption used in the risk assessment. These results suggest that a change in the complete leachate mixing assumption could raise the receptor well concentrations (and therefore risks) for metal constituents whose Kd values decrease with increasing pH.

Table 4-29. Change in Peak Receptor Well Concentrations for Ash Disposed in Landfills Assuming Leachate Does Not Mix in Aquifer

Percentile of Peak Concentration	Percent Change in Peak Concentration	
	As(III)	As(V)
10	0.00%	0.00%
20	0.00%	0.00%
30	0.91%	0.00%
40	0.25%	0.00%
50	0.31%	2.28%
60	0.00%	15.57%
70	0.23%	57.97%
80	0.00%	18.31%
90	0.00%	11.75%

Goethite Versus Hydrous Ferric Oxide Sorbent. The choice of iron sorbent is important because goethite is a much poorer adsorbent than hydrous ferric oxide and will result in larger leachate contaminant concentration. With respect to the use of goethite versus the use of hydrous ferric oxide, EPA had discussions with Dr. David Dzombak and Dr. Samir Mathur (developer of the goethite database). In these discussions, the group discussed the sorbent question extensively, and EPA chose to use goethite rather than hydrous ferric oxide as a best estimate that would not underestimate risk. However, because actual CCW disposal sites could have hydrous ferric oxide present in their soils, the risks for arsenic could be overestimated.

Multiple Constituent Exposures. The individual human risk from each CCW constituent was considered separately in this analysis. However, the CCW waste constituent database and recent field studies such as U.S. EPA (2006c) and U.S. EPA (2008c) suggest that exposure to multiple constituents is highly likely. Because multiple constituent exposure may be synergistic depending on the constituents, certain constituent combinations may cause adverse health impacts that a single-constituent approach may underestimate. However, the quantitative human health benchmarks used by EPA are based on the toxicity of individual chemicals. With only one carcinogen present in CCW (arsenic), it was not necessary to add carcinogenic risks. Noncarcinogenic risks can be added only for chemicals with toxic effects on the same target organs, and this could have been done for fish and drinking water ingestion risks by accounting for transit time and adding HQs for contaminants with noncancer effects on the same target organs that arrive at the same time to the receptor point.

However additivity across chemicals was not considered in this risk assessment; neither was synergism or antagonism. Noncancer hazard may, therefore, be under- or overestimated. Nevertheless, risks were high enough from human exposure to single chemicals (notably arsenic, the single carcinogen) that this would not have changed the basic conclusion of the risk assessment: that there are potentially significant risks to human health from CCW disposal in landfills and surface impoundments.

4.4.3 Parameter Uncertainty and Variability

Parameter uncertainty occurs when (1) there is a lack of data about the values used in the equations, (2) the data that are available are not representative of the particular instance being modeled, or (3) parameter values have not been measured precisely or accurately because of limitations in measurement technology. Random, or sample, errors are a common source of parameter uncertainty that is especially critical for small sample sizes, as illustrated by the FBC waste results discussed in **Section 4.1.3.2**. More difficult to recognize and address are nonrandom or systematic errors that can bias the analyses from sampling errors, faulty experimental designs, or bad assumptions.

Spatial and temporal variability in parameters used to model exposure account for the distribution in the exposed population. For example, the rainfall or precipitation rates used to calculate infiltration and recharge to groundwater are measured daily by the National Weather Service at many locations throughout the United States, and statistics about these parameters are well documented. Although the distributions of these parameters may be well known, their actual values vary spatially and temporally and cannot be predicted exactly. Thus, the annual average infiltration rates used in the source model for a particular climate station provide information on average conditions appropriate for this analysis. Additionally, using data from multiple climate stations located throughout the United States can account for some, but not all, spatial variability.

4.4.3.1 Waste Concentrations

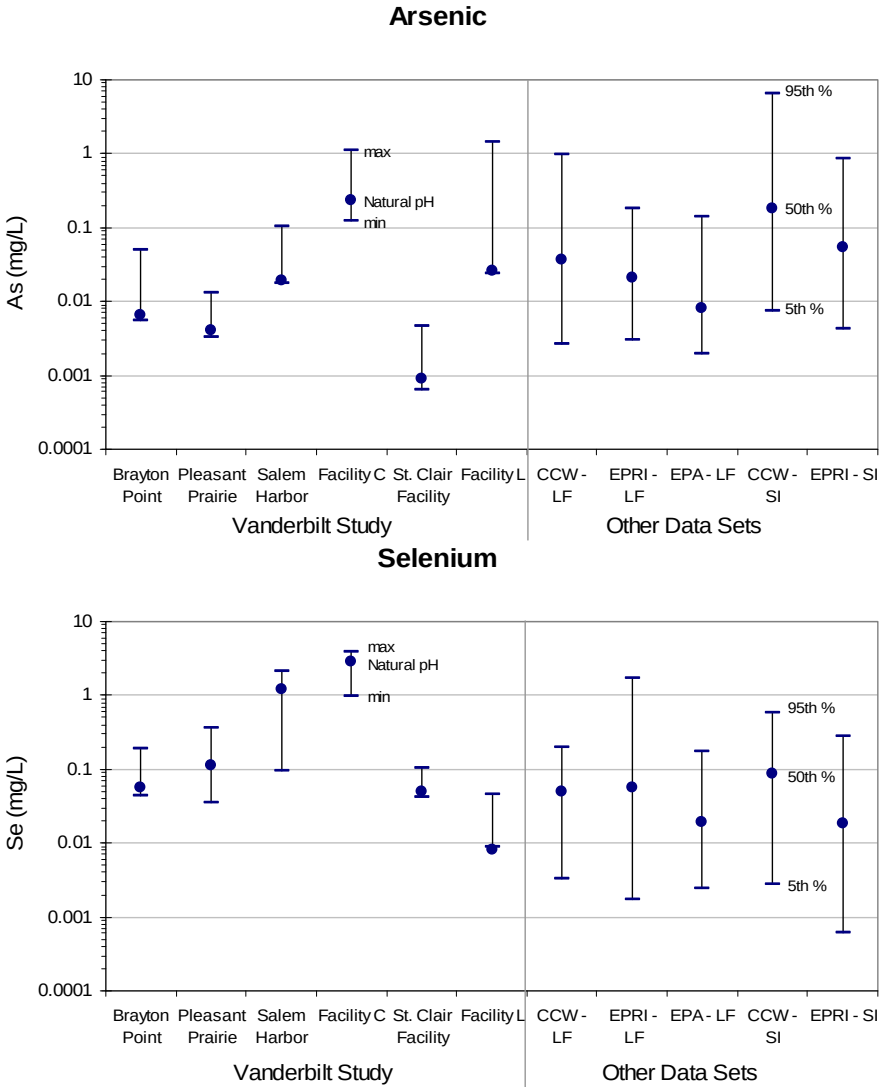
The CCW constituent database used to represent CCW total waste and waste leachate concentrations is arguably the most important data set in terms of driving the risk assessment results. The constituent data are subject to two primary uncertainties beyond the normal sampling and analysis uncertainty associated with environmental measurements: (1) the appropriateness of the landfill leachate data used in the analysis and (2) high percentages of nondetect analyses for some CCW constituents.

Appropriateness of Leachate Data. The CCW leachate data were collected from a varying number of sites using a variety of methods. The available landfill data were largely derived from the TCLP, a laboratory test designed to estimate leachate concentrations in municipal solid waste (MSW) landfills. The TCLP has been shown to both over- and underpredict leachate concentrations for other waste disposal scenarios, so the use of the TCLP data to represent CCW leachate is another source of uncertainty. However, as noted below, the TCLP data do appear to encompass the range of variability in CCW leachate concentrations that have been measured in more recent studies.

Surface impoundment leachate is represented by porewater measurements taken beneath actual impoundments, which should more closely represent the leachate seeping from the bottom of the impoundment than would bulk surface impoundment waste concentrations. The porewater is in direct contact with the waste, so these concentrations should typically be at least as great as concentrations in the bulk surface impoundment. However, although these porewater data arguably should better represent leachate concentrations, they are fewer in number than the landfill data and therefore subject to uncertainty as to how representative they are of all CCW

wastes. Results for surface impoundments for antimony, mercury, and thallium are not presented due to the paucity of leachate data (1 or 2 sites, and 11 or fewer values).

Since the CCW risk assessment was conducted in 2003, EPA-sponsored research conducted by Vanderbilt University has improved the scientific understanding of the generation of leachate from CCW, in particular for mercury, arsenic, and selenium (U.S. EPA, 2006c; U.S. EPA, 2008c). **Figure 4-2** plots the results from U.S. EPA (2006c) for arsenic and selenium, along with data from EPA's Leach2000 database and EPRI (as provided in U.S. EPA, 2006c) against the data used for landfills and surface impoundments used in the CCW analysis.



Key to data sets:

Vanderbilt	=	U.S. EPA (2006c)
CCW	=	CCW Constituent Database (this analysis)
EPRI	=	EPRI Leachate data (from U.S. EPA, 2006c)
EPA	=	Leach 2000 data (from U.S. EPA, 2000)
LF	=	landfills
SI	=	surface impoundments

Figure 4-2. Comparison of CCW leachate data with other leachate data in U.S. EPA (2006c).

For the 2006 Vanderbilt leaching study report, data are provided for each ash tested, with the minimum, maximum, and value at natural pH plotted on the chart. Percentile values (95th, 50th, 5th) are plotted for the compiled data sets (EPA, EPRI, and CCW), and mercury was not modeled for landfills because of a high number of nondetects.

For arsenic, the CCW values bracket the range found in the other studies. Selenium values also agree fairly well for CCW landfill data, although the CCW landfill values appear to be lower than some of the values from the other studies, suggesting that selenium risks may have been somewhat underestimated for landfills in this analysis. This is significant even though selenium risks from landfills were not above an HQ of 1 in this analysis, because selenium is often reported as a constituent of concern (along with arsenic and boron) in CCW damage cases (U.S. EPA, 2000, 2003e; Lang and Schlictmann, 2004; Zillmer and Fauble, 2004).

U.S. EPA (2008c) extends the work in U.S. EPA (2006c) to include laboratory leaching studies of 23 CCWs sampled from 8 coal combustion power plants. Wastes tested included fly ash, scrubber sludges, and gypsum. All of the metals addressed in this risk assessment were measured in the laboratory leaching tests.

Similar to Figure 4-2 above, Figures 46–59 on pages 77–86 in U.S. EPA (2008c) compare constituent concentration ranges in their laboratory CCW extracts to ranges reported by other CCW leachate data compilations, including the constituent data from this risk assessment. These graphs are not repeated here, but the conclusions are similar to the U.S. EPA (2006c) comparisons, in that the ranges of metals concentrations generally plot within the range reported for the laboratory tests, especially with fly ash and flue gas desulfurization sludges. For ash codisposed with coal refuse metal, concentrations tend to be an order of magnitude or more greater than the wastes studied in U.S. EPA (2008c), which did not include such codisposed wastes. Only two CCW metals plot largely outside the range for fly ash. Barium fly ash concentrations from the CCW risk assessment are an order of magnitude or more lower than those reported by U.S. EPA (2008c), and lead concentrations in the fly ash and FGD wastes modeled in this risk assessment are one to two orders of magnitude above those plotted in U.S. EPA (2008c). The latter may be an artifact of the predominance of TCLP measurements in the CCW constituent database, because the acetate buffer in the TCLP can be especially effective in complexing lead compounds into the extract solution. Finally, a few of the Vanderbilt measurements for molybdenum and selenium are above the range modeled in the CCW risk assessment.

The fact that the 2006 and 2008 Vanderbilt results are in general agreement with the CCW arsenic and selenium levels does help allay concerns that the TCLP CCW leachate values used in the analysis markedly overestimate or underestimate the concentrations actual CCW leachate.

Mercury and Nondetect Analyses. For certain of the CCW constituents addressed in this analysis, the CCW leachate database contains a large number of nondetect measurements (concentrations below an analytical instrument's ability to measure). **Table 4-30** illustrates this point by showing, by WMU type and chemical, the overall percent of nondetect values for each

chemical and the percent of site-averaged values[11] that are composed entirely of nondetect measurements. Although some constituents have a large number of nondetect values, many of those could still be modeled (substituting half the detection limit for nondetect values). Where there are detections for a chemical, the specific substitute value used for nondetect values does not affect the upper percentile risks, because the upper percentile risks are associated with the higher, detectable source concentrations in the distribution rather than the lower source concentrations associated with nondetect values. Values for nondetects will be in the lower percentiles whether they are half the detection limit or some other value.

Table 4-30. Proportion of Nondetect Analyses for Modeled CCW Constituents

Chemical[a]	Measurements		Sites	
	Number	% nondetects	Number	% with all nondetects
Landfills				
Aluminum	397	18%	61	5%
Antimony	496	50%	66	41%
Arsenic	1,182	49%	128	20%
Barium	1,225	11%	126	5%
Boron	930	8%	83	2%
Cadmium	1,237	50%	124	31%
Cobalt	559	56%	52	19%
Lead	1,109	60%	125	30%
Mercury	***974***	***91%***	***101***	***58%***
Molybdenum	373	24%	58	10%
Nitrate/Nitrite	141	48%	20	15%
Selenium	1,227	49%	131	17%
Thallium	402	60%	40	45%
Surface Impoundments				
Aluminum	158	10%	16	6%
Antimony	***11***	***100%***	***2***	***100%***
Arsenic	155	16%	16	6%
Barium	161	14%	16	13%
Boron	164	7%	171	6%
Cadmium	164	68%	16	50%
Cobalt	49	59%	4	50%
Lead	138	78%	14	36%
Mercury	***1***	***100%***	***1***	***100%***
Molybdenum	161	37%	17	24%
Nitrate/Nitrite	267	59%	14	7%
Selenium	140	33%	15	20%

(continued)

[11] As explained in **Appendix A**, the CCW risk assessment used site-averaged constituent concentrations. That is, an average value was used when there were multiple measurements for a chemical at a particular site.

Proportion of Nondetect Analyses for Modeled CCW Constituents (continued)

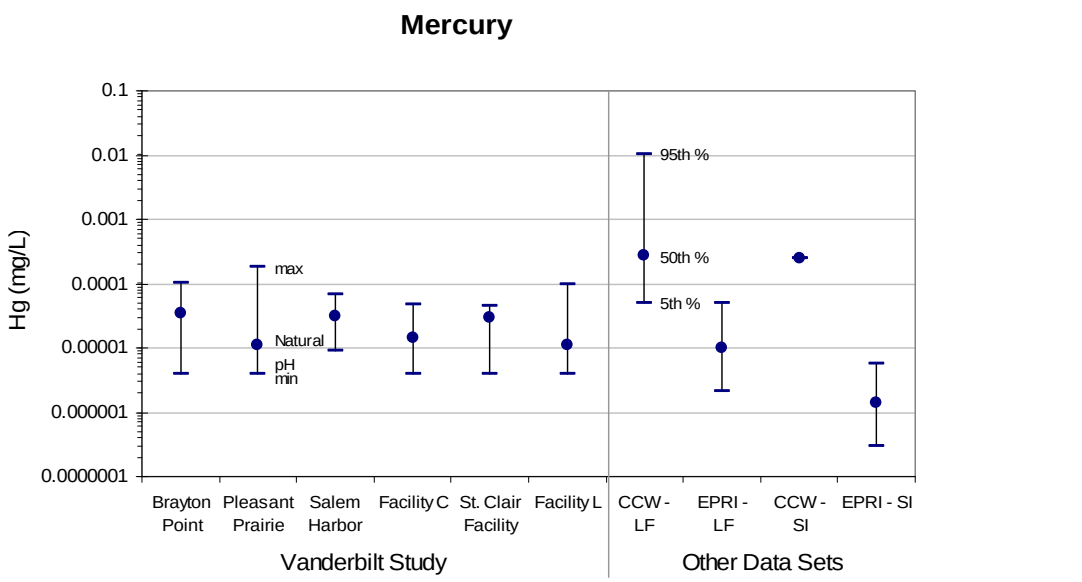
Chemical[a]	Measurements		Sites	
	Number	% nondetects	Number	% with all nondetects
Thallium	***11***	***100%***	***2***	***100%***

[a] Results for constituents shown in ***bold italics*** were not presented in this report because of high detection limits or limited data.

Constituents that could not be addressed in this analysis because of a very high number of nondetects (i.e., more than 90 percent of measurements) included mercury (for landfills and surface impoundments) and thallium and antimony (for surface impoundments only). Mercury is of particular interest because it is the only constituent with significant concern through the fish consumption pathway, and because there is the potential for mercury concentrations in CCW to increase as flue gas mercury controls are installed on coal-fired power plants in response to the Clean Air Interstate Rule (CAIR) and the Clean Air Mercury Rule (CAMR). However, analysis of the effect of mercury emission controls was outside the scope of the risk assessment, which was to evaluate current waste disposal conditions, not potential future changes due to emission controls.

Recent work by Vanderbilt University (U.S. EPA, 2006c, 2008c) sheds some light on mercury concentrations in leachate from some CCWs. **Figure 4-3** plots the CCW distribution of mercury concentrations (assuming half the detection limit for mercury values below detection) against results from the Vanderbilt work and recent data collected by EPRI (from U.S. EPA, 2006c; results are similar in U.S. EPA, 2008c). Assuming half the detection limit, the CCW mercury leachate values are about an order of magnitude or more higher than the Vanderbilt or EPRI data. With a single CCW leachate analysis available for surface impoundments, it is difficult to draw firm conclusions, but the concentration value is above the maximum value shown in the other studies. In short, the mercury levels in the CCW database are not useful because of high detection limits. In addition, the Vanderbilt study found that older mercury analyses, such as the ones in the CCW database, could be biased high because of cross-contamination issues.

Finally, U.S. EPA (2006c) and preliminary results of ongoing EPA studies (e.g., U.S. EPA, 2008c) suggest that both mercury levels and mercury leachability in CCW can vary depending on the flue gas mercury controls used at a power plant.



Key to data sets:

Vanderbilt	=	U.S. EPA (2006c)
CCW	=	CC Constituent Database (this analysis)
EPRI	=	EPRI Leachate data (from U.S. EPA, 2006c)
EPA	=	Leach 2000 data (from U.S. EPA, 2000, as cited in U.S. EPA, 2006c)
LF	=	landfills
SI	=	surface impoundments

Figure 4-3. CCW mercury concentrations compared with other leachate data.

4.4.3.2 WMU Locations and Characteristics

The locations of the specific sites in the United States where CCW is disposed are known, and EPA used the soil and climatic characteristics of these sites in the Monte Carlo analysis. Because most locations were facility front gates or centroids, the exact location of the CCW landfill or surface impoundment was not known. To account for this uncertainty, soil data were collected for an area around the plant and soil type distributions were sampled in the Monte Carlo analysis. Climate center assignments were combined with the soil texture distributions to select infiltration and recharge rates to use in the analysis.

WMU area, depth, volume, and liner type were not varied in the Monte Carlo analysis because values for these variables were known from the EPRI survey data. More uncertain parameters, such as depth below grade, were varied within reasonable ranges. These data were used in the source model calculations to generate the distribution of environmental releases used by the fate and transport modeling.

Three standard WMU liner scenarios (clay, composite, and unlined) were assigned to each facility based on best matches to data in the EPRI survey on liner type. Infiltration through these liners was then modeled using assumptions, models, and data developed in support of EPA's Industrial Subtitle D guidance. How well these assumptions and models represent the performance of CCW WMU landfills and surface impoundments is an uncertainty in this analysis.

With respect to the clay liners, the 2009 risk assessment used the assumption that compact clay liners were designed to have a hydraulic conductivity of 1×10^{-7} cm/sec. This is consistent with EPA's Industrial D Guidance, which states that "clay liners should be at least 2 feet thick and have a maximum hydraulic conductivity of 1×10^{-7} cm/sec" (U.S. EPA, 2006d). However, clay liners designed to meet a 1×10^{-7} cm/sec hydraulic conductivity could perform differently in practice. In one liner study (Moo-Young et al., 2004), a small set of clay-lined landfills were found to have field hydraulic conductivities ranging from 2×10^{-9} to 4.4×10^{-8} cm/sec and a small set of surface impoundments were found to have field hydraulic conductivities ranging from 3×10^{-6} to 3.2×10^{-5} cm/sec. Thus, the assumption of clay liners performing at 1×10^{-7} cm/sec could lead to an under- or over-estimate of actual risks.

Composite liners would also not be expected to perform consistently over 10,000 years as was assumed in the model. Instead, the liner would eventually perform at the level of the clay layer once the synthetic layer had deteriorated. This simplification is likely to lead to an underestimate of composite liner risks.

4.4.3.3 Fate and Transport Model Variables

The parameter values required to model contaminant fate and transport in groundwater were obtained from site-specific, regional, and national databases. Hydrogeologic environment was assigned to each site, based on geologic maps and soil conditions; where assignments were uncertain, two or three settings might be used in the Monte Carlo analysis. Because aquifer properties are highly variable and uncertain, reasonable sets of aquifer properties were selected, based on hydrogeologic environment, from a hydrogeologic database.

Receptor Location (Drinking Water Wells). The sensitivity analysis (**Section 4.3**) showed that distance of a receptor from the contaminant source is an important influence on media concentration, especially for contaminants that strongly sorb to soil and aquifer materials. For the groundwater-to-drinking-water pathway, receptor location was represented as the distance and position, relative to a contaminant plume, of residential drinking water wells from the WMU. Because no data were readily available on the distance of CCW disposal sites from residential wells, EPA used data from a survey of well distances from MSW landfills. Whether or not this is an accurate representation of well distance for CCW landfills and surface impoundment is an uncertainty in this analysis. EPA believes that the MSW well distance distribution used is protective for CCW landfills and surface impoundments. See **Appendix C**, **Section C.2**, for more details.

Location and Characteristics of Waterbodies. One aspect of the site configuration of particular relevance to the aquatic food chain modeling is the locations and characteristics of the waterbodies. The size of the waterbodies (and the distance from the WMU) affects constituent concentrations and loadings predicted for that waterbody. The distance from the WMU to the waterbody was based on an empirical distribution of measurements, taken from actual CCW sites, of the distance from the edge of the WMU to the nearest stream or lake. The uncertainty posed in this analysis is the sampling of this distribution as compared to a more certain measurement of the actual distance at each CCW site. Surface water variables, including flow and water quality parameters, were collected for the stream reach being modeled, or for a larger hydrologic region where data were not available for a particular reach.

Waterbodies Intercepting the Groundwater Plume. As discussed in **Section 3.7**, mass is not actually removed from the groundwater when the plume is intercepted by a surface waterbody. Therefore, in cases where wells are located beyond an intersecting surface water body, the draft risk assessment may not account for interactions between surface water and groundwater. Examining the input database, EPA notes that approximately two-thirds (69%) of the Monte Carlo runs contained such an intersecting surface waterbody. Thus, the 50th percentile results may overestimate groundwater risks to these receptors. However, because the WMUs with closer receptor wells exhibited higher risks on average, the 90th percentile results are not likely to be significantly affected.

Environmental Parameters. Uncertainties related to environmental parameters (soil, aquifer, surface water, climate data) have already been mentioned. The parameters with the largest impact on results are aquifer hydraulic conductivity and gradient, which were selected from a national database of aquifer properties.

Fish Bioconcentration and Bioaccumulation Factors. For fish consumption, exposure dose was calculated using BCFs to estimate the transfer of pollutants from environmental media into fish. Uncertainty is associated with models used to estimate BCFs for aquatic biota. Aquatic BCFs are developed by dividing measured concentrations in aquatic biota by total surface water concentrations. **Appendix J** lists the bioconcentration and bioaccumulation parameters used in the risk assessment, along with their sources.

4.4.3.4 Exposure and Risk Modeling Variables

Exposure parameters and benchmarks for human and ecological risk also contribute to parameter variability and uncertainty.

Human Exposure Factors. Individual physical characteristics, activities, and behavior are quite different, and thus the exposure factors that influence the exposure of an individual, including ingestion rate, body weight, and exposure duration, are quite variable. Exposure modeling relies heavily on default assumptions concerning population activity patterns, mobility, dietary habits, body weights, and other factors. The probabilistic assessment for the adult and child exposure scenario addressed the possible variability in the exposure modeling by using statistical distributions for these variables for each receptor in the assessment: adult and child resident and adult and child recreational fisher. Data on fish consumption rates were not available for children of recreational anglers; thus the adult recreational angler data were used for children in this analysis, which could overestimate risk from this pathway for children. For all exposure factors varied, a single exposure factor distribution was used for adults for both males and females. For child exposures, one age (age 1) was used to represent the age at the start of exposure, because this age group was considered to be most sensitive for most health effects.

The *Exposure Factors Handbook* (U.S. EPA, 1997c,d,e) provides the current state of the science concerning exposure assumptions and represents EPA's current guidance on exposure data, and it was used throughout this assessment to establish statistical distributions of values for each exposure parameter for each receptor. The *Exposure Factors Handbook* has been carefully reviewed and evaluated for quality. EPA's evaluation criteria included peer review, reproducibility, pertinence to the United States, currency, adequacy of the data collection period,

validity of the approach, representativeness of the population, characterization of the variability, lack of bias in study design, and measurement error. There are some uncertainties, however, in the data that were used.

Site-specific fish consumption rate data were not available, but the Maine study data, where anglers fished from streams, rivers, and ponds, were consistent with the modeling scenarios used in this risk analysis and provided the detailed percentile data required for a probabilistic analysis. However, applying Maine angler consumption rates to other parts of the country may under- or overestimate exposures.

EPA's child-specific exposure guidance has been recently finalized (U.S. EPA, 2008b) but was not used in the risk assessment because the water consumption rates and body weights provided in the *Child-Specific Exposure Factors Handbook* (U.S. EPA, 2008b) do not differ significantly from those found in the 1997 *Exposure Factors Handbook* and would not have changed the results, but the use of the 1997 values may contribute some parameter uncertainty. One exception is the distribution of child fish consumption rates used. Here, U.S. EPA (2008b) consumption rates are higher than the 1997 rates used in the analysis. This introduces uncertainty into the analysis, and likely underestimates risks in the fish consumption pathway.

As is customary for EPA's RCRA risk assessments, human exposure factor data were not correlated (i.e., for each modeling run, each exposure factor was selected from its distribution independently), introducing some uncertainty because it is possible to select, for example, a high drinking water rate with a small body weight. However, although a specific modeling run may have had an unrealistic combination of exposure factors, the large number of Monte Carlo iterations performed (10,000) ensures that this is unlikely to significantly affect the risk assessment results.

Diet Assumptions for Ecological Receptors. National-scale assessments often assume maximum intake of contaminated prey in the diets of primary and secondary consumers (i.e., 100 percent of the diet originates from the contaminated area). Under field conditions, many receptors are opportunistic feeders with substantial variability in both the type of food items consumed and the geospatial patterns of feeding and foraging. The actual proportion of wildlife receptors' diets that would be contaminated depends on a number of factors such as the species' foraging range, quality of food source, season, intra- and interspecies competition. Consequently, the exclusive diet of contaminated food items tends to provide a very high-end estimate of potential risks.

Human Health Benchmarks. The uncertainties generally associated with human health benchmarks are discussed in detail in EPA's *Guidelines for Carcinogen Risk Assessment* (U.S. EPA, 2005), and IRIS (U.S. EPA, 2009a). EPA defines the RfD as "an estimate (with uncertainty spanning perhaps an order of magnitude) of a daily exposure to the human population (including sensitive subgroups) that is likely to be without appreciable risk of deleterious effects during a lifetime" (U.S. EPA, 1994, 2009a). RfDs are based on an assumption of lifetime exposure and may not be appropriate when applied to less-than-lifetime exposure situations (U.S. EPA, 2009a). The CSF is an upper-bound estimate of the human cancer risk per mg of chemical per kg body weight per day. Because exposures were often less than lifetime, some uncertainty was introduced in the noncancer hazard and cancer risk estimates.

EPA routinely accounts for uncertainty in their development of RfDs and other human health benchmarks. Uncertainty and variability in the toxicological and epidemiological data from which RfDs were derived are accounted for by applying uncertainty factors. Some of these uncertainties include those associated with extrapolation from animals to humans, from LOAELs to NOAELs, and from subchronic to chronic data, and to account for sensitive subpopulations. If certain toxicological data are missing from the overall toxicological database (e.g., reproductive data), EPA accounts for this by applying an uncertainty factor.

Table 4-31 presents IRIS uncertainty factors for the RfDs for the CCW constituents that showed HQs greater than 1 in the risk assessment, along with the highest HQ observed and the disposal scenario for which this HQ was observed. IRIS defines uncertainty factors as follows:

> "Uncertainty factors (UFs) are one of several, generally 10-fold, default factors used in operationally deriving the RfD from experimental data. The factors are intended to account for (1) variation in susceptibility among the members of the human population (i.e., inter-individual or intraspecies variability); (2) uncertainty in extrapolating animal data to humans (i.e., interspecies uncertainty); (3) uncertainty in extrapolating from data obtained in a study with less-than-lifetime exposure (i.e., extrapolating from subchronic to chronic exposure); (4) uncertainty in extrapolating from a LOAEL rather than from a NOAEL; and (5) uncertainty associated with extrapolation when the database is incomplete."[12]

The constituent-specific uncertainty factors for the CCW constituents in Table 4-31 are discussed further in the source documents (e.g., IRIS) for the individual human health benchmarks used in the analysis, which are referenced in **Appendix G**. In general, EPA human health benchmarks are derived using a health-protective approach. These uncertainty factors can be considered when evaluating the constituent-specific risks presented in this document, but only in the context of the above definitions and the information presented in IRIS for each chemical.

The hierarchy of data sources that was implemented for this analysis was based largely on the rigor of review that a benchmark has received. Methodologies evolve over time, with improvements in existing methods and the development of new health benchmark practices (e.g., benchmark dose methodology). As a result, the magnitude of a given benchmark can either increase or decrease, or a given benchmark can appear or disappear in a toxicity benchmark database. An example of the latter situation, disappearance of a toxicity benchmark, occurred during the development of this report. The human health benchmark for thallium was withdrawn from IRIS in late September 2009. The modeling results, including the noncancer human health effects estimates, were retained in this document to reflect the potential for thallium releases from CCW WMUs. EPA has decided to retain these estimates, in light of the National Academy of Sciences' (NAS's) 2008 report entitled *Science and Decisions: Advancing Risk Assessment* (NAS, 2008). In that report's recommendations, the authors noted that absence of certain information from a risk characterization can result in the missing information being overlooked during the decision making process. Evidence that relatively small quantities of thallium can be

[12] http://www.epa.gov/ncea/iris/help_gloss.htm#u

fatal to humans[13] leads EPA to conclude that omitting the thallium results from this report might cause thallium's existence in coal combustion residues to be overlooked during the risk management decision making, and thus EPA has chosen to retain those modeling results in this report.

Table 4-31. RfD Uncertainty Factors for and Benchmark Confidence for CCW Constituents with HQs Over 1

Constituent	RfD (mg/kg-day)	Source	Uncertainty Factor	Benchmark Confidence	Highest CCW HQ	CCW Scenario for Highest HQ
Antimony	4.0E-04	IRIS	1,000	low	3	GW-DW, FBC wastes, clay-lined landfills
Boron	2.0E-01	IRIS	66	high	7	GW-DW, Conventional CCW, unlined SIs
Cadmium	5.0E-04	IRIS	10	high	9	GW-DW, Codisposed CCW, unlined SIs
Cobalt	3.0E-04	PPRTV	1,000	low	500	GW-DW, Codisposed CCW, unlined SIs
Molybdenum	5.0E-03	IRIS	30	medium	8	GW-DW, Conventional CCW, unlined SIs
Selenium	5.0E-03	IRIS	3	high	3	GW-SW, Conventional CCW, unlined SIs
Thallium	8.0E-05	IRIS	3,000	low	4	GW-DW, FBC wastes, clay-lined landfills

Most health benchmarks used in this analysis were from IRIS. Human health benchmarks in IRIS have been subjected to rigorous internal and external reviews and represent Agency-wide consensus human health risk information. However, some benchmarks in IRIS are quite dated. Provisional human health benchmarks derived by the Superfund Technical Support Center have been peer reviewed and are used where there is no IRIS value.

Chemical-specific health benchmarks were used for all constituents assessed in the analyses. However, the RfD for fluoride was based on fluorine; the RfDs for mercuric chloride and methyl mercury were used as surrogates for elemental mercury from food, soil, and water ingestion, and fish ingestion, respectively; and the RfD for thallium was based on thallium chloride. The use of these surrogate data is not thought to have introduced any significant uncertainty. Human health benchmarks are not age-specific, and therefore, were applied to both child and adult receptors, thereby introducing some uncertainty.

EPA used the drinking water MCL for lead to estimate risks from drinking water exposure. The IEUBK model may better quantify risk for a young child exposed to lead; therefore, use of the MCL may introduce some uncertainty. However, risks from lead exposure were relatively low, well below the risk criterion for landfills and at or slightly above the risk criterion for surface impoundments, and did not drive the risk assessment conclusions.

[13] "Temporary hair loss, vomiting, and diarrhea can also occur and death may result after exposure to large amounts of thallium for short periods. Thallium can be fatal from a dose as low as 1 gram." (ATSDR, 1992)

Ecological Criteria. CSCLs were developed for constituents when sufficient data were available. In many cases, sufficient data were unavailable for a receptor/constituent combination, and therefore, the potential risk to a receptor could not be assessed. In particular, insufficient data were available to derive chronic effects CSCLs for amphibians. Because the risk results can only be interpreted within the context of available data, the absence of data cannot be construed to mean that adverse ecological effects will not occur.

In addition to the effects of data gaps on ecological benchmarks, the ecological criteria tend to be fairly conservative because the overall approach is based on "no effects" or "lowest effects" study data. In site-specific assessments, a *de minimis* effects approach is often replaced with an effects level similar to natural population variability (e.g., sometimes as high as a 20 percent effects level). As a result, the CSCLs used in this analysis are likely to overestimate risks for representative species and communities assumed to live in surface waters impacted by CCW WMUs. Because the difference between a LOAEL and a NOAEL is often about a factor of 10, an HQ exceedance of roughly 10 may not be ecologically significant. In contrast, CSCLs based on no effects data that are developed for the protection of threatened and endangered species are presumed to be protective.

4.5 Summary and Conclusions

CCW risk assessment results at the 90th percentile suggest that the management of CCW in unlined or clay-lined WMUs result in risks greater than 1 in 100,000 for excess cancer risk to humans or an HQ greater than 1 for noncancer effects to both human and ecological receptors. Key risk findings include the following:

- For humans exposed via the groundwater-to-drinking-water pathway, risks from clay-lined units that dispose CCW or CCW comanaged with coal refuse are lower than those for unlined units. However, the 90th percentile risks for clay-lined units are still well within or above the range of concern (10^{-6} to 10^{-4}) for cancer risk and above an HQ of 1 for noncarcinogens. For example, arsenic III cancer risks in clay-lined units range from 1 in 5,000 for landfills to 9 in 10,000 in surface impoundments. The thallium HQ was as high as 2 for clay-lined landfills, and the clay-lined surface impoundment HQ was as high as 200 for cobalt and 4 for boron.

- Arsenic was the constituent with the highest risk for landfills. Clay-lined landfills presented 90th percentile risks above an excess cancer risk of 1 in 100,000 for arsenic (risks as high as 1 in 5,000) and an HQ of 1 for thallium (HQ of 2). When landfills are unlined, they also present risk above an HQ of 1 for antimony and molybdenum, each with an HQ of 2. Here, arsenic cancer risks were as high as 1 in 2,000. Clay-lined FBC landfills also presented 90th percentile risks above and HQ of 1 for antimony (HQ = 3) and thallium (HQ = 4) and showed excess cancer risks of 3 in 50,000 for arsenic. However, unlined FBC landfills differed in that they only exceeded a 1 in 100,000 excess cancer risk for arsenic.[14] At the 50th percentile, arsenic III from CCW codisposed with

[14] As modeled, unlined FBC units showed less risk than clay-line FBC units.

coal refuse unlined landfills showed an excess cancer risk of 1 in 50,000: all noncarcinogenic constituents were well below an HQ of 1.

- Arsenic and cobalt were the constituents with the highest risks for surface impoundments, with risks as high as 1 in 50 and an HQ of 500, respectively, for unlined units. Clay-lined surface impoundments presented 90th percentile cancer risks above 1 in 100,000 for arsenic (7 in 1,000 cancer risk), HQs above 1 for boron (HQs as high as 4), cadmium (HQ as high as 3), cobalt (HQ as high as 200), molybdenum (HQ as high as 5), and nitrate (an MCL-based HQ as high as 10). When surface impoundments are unlined, they also show risk above an HQ of 1 for lead (HQ of 9) and selenium (HQ of 2). Here, arsenic cancer risks are as high as 1 in 50, and cobalt had HQs as high as 500. The only 50th percentile surface impoundment results that exceeded the risk range or HQ criterion were arsenicand cobalt. Here, unlined units had arsenic cancer risks as high as 6 in 10,000 while clay-lined units had arsenic cancer risks as high as 1 in 5,000. Cobalt HQs were as high as 20 and 6 for unlined and clay-lined surface impoundments, respectively.

- For the groundwater-to-drinking-water pathway, composite liners, as modeled in this assessment, effectively reduce risks from all constituents to below a cancer risk of 1 in 100,000 and an HQ of 1 for both landfills and surface impoundments at the 90th and 50th percentiles.

- For the groundwater-to-drinking-water pathway, arrival times of the peak concentrations at a receptor well are much longer for landfills (hundreds or thousands of years) than for surface impoundments (most less than 100 years).

- For humans exposed via the groundwater-to-surface-water (fish consumption) pathway, unlined and clay-lined surface impoundments posed risks above an excess cancer risk of 1 in 100,000 and an HQ of 1 at the 90th percentile. For CCW managed alone in surface impoundments, these exceedences came from selenium (HQs of 3 and 2), while for CCW comanaged with coal refuse these exceedences came from arsenic (3 in 100,000 and 2 in 100,000 excess cancer risks for unlined and clay-lined units). All 50th percentile surface impoundment risks are below a cancer risk of 1 in 100,000 and an HQ of 1. No constituents pose risks above these risk levels for landfills (including FBC landfills) at the 90th or 50th percentile for the fish consumption pathway.

- Waste type has a much larger effect when wastes are managed in surface impoundments than when they are managed in landfills. In the case of surface impoundments, some constituents (boron, molybdenum, nitrate, and selenium) presented higher risks from CCW managed alone. However, others (arsenic, cadmium, cobalt, and lead) presented higher risks when CCW is comanaged with coal refuse, because of their association with the sulfide minerals concentrated in the refuse.

- The higher risks for surface impoundments than landfills are likely due to higher waste leachate concentrations and the higher hydraulic head from the impounded liquid waste. This is consistent with damage cases reporting wet handling as a factor that can increase risks from CCW management.

- For ecological receptors exposed via surface water, risks for landfills exceed an HQ of 1 for boron (HQ of 281 for unlined and 78 for clay-lined), lead (HQ of 8 for unlined), and selenium, arsenic, and barium (HQs of 2) at the 90th percentile, but 50th percentile HQs are well below 1. For surface impoundments, 90th percentile risks for several constituents (boron, lead, arsenic, selenium, cobalt, and barium) exceed an HQ of 1, with boron showing the highest risks (HQ over 2,000). Only boron exceeds an HQ of 1 at the 50th percentile (HQ = 7 for unlined surface impoundments). The HQs over 1 for boron and selenium are consistent with reported ecological damage cases, which include impacts to waterbodies through the groundwater-to-surface-water pathway.

- For ecological receptors exposed via sediment, 90th percentile risks exceed an HQ of 1 for both landfills and surface impoundments because certain CCW constituents strongly sorb to sediments in the waterbody. Here, the 90th percentile HQ for lead was 58 for unlined landfills and clay-lined surface impoundments, and 311 for unlined surface impoundments. For arsenic, HQs were 11 and 3 for unlined and clay-lined landfills, and 127 and 55 for unlined and clay-lined surface impoundments. Cadmium had HQs of 5 for unlined landfills, and 30 and 9 for unlined and clay-lined surface impoundments. Antimony had an HQ of 2 for unlined landfills. Composite lined surface impoundments also had risks above an HQ of 1 for lead (HQ of 4), arsenic (HQ of 31), and cadmium (HQ of 2). The 50th percentile risks are an order of magnitude or more below an HQ of 1 for ecological receptors exposed via sediments.

Sensitivity analysis results indicate that for most of the scenarios evaluated (over 70 percent), the risk assessment model was most sensitive to parameters related to the contaminant source and groundwater flow and transport: WMU infiltration rate, leachate concentration, and aquifer hydraulic conductivity and gradient. For strongly sorbing contaminants (such as lead and cadmium), variables related to sorption and travel time (adsorption coefficient, depth to groundwater, receptor well distance) are also important.

One of the most sensitive parameters in the risk assessment (infiltration rate) is greatly influenced by whether and how a WMU is lined. The 1994–2004 DOE/EPA survey results (U.S. DOE, 2006) do not include information on how many unlined facilities are still operating today, but do indicate that more facilities are lined today than were in the 1995 EPRI survey data set on which this risk assessment was based. This suggests that the risks from future CCW disposal facilities are likely to be lower than the results presented in this report.

There are uncertainties associated with the CCW risk assessment, but scenario uncertainty (i.e., uncertainty about the environmental setting around the plant) has been minimized by basing the risk assessment on conditions around existing U.S. coal-fired power plants around the United States. Uncertainty in environmental setting parameters has been incorporated into the risk assessment by varying these inputs within reasonable ranges when the exact value is not known. Uncertainty in human exposure factors (such as exposure duration, body weight, and intake rates) has also been addressed through the use of national distributions.

Some uncertainties not addressed explicitly in the risk assessment have been addressed through comparisons with other studies and data sources.

- **Appropriateness of CCW leachate data.** Data on another highly sensitive parameter, leachate (porewater) constituent concentration, were available and used for CCW surface impoundments. However, available data for landfills were mainly TCLP analyses, which may not be representative of actual CCW leachate. Comparisons with recent (2006 and 2008) studies of coal ash leaching processes show very good agreement for arsenic. However, although the selenium CCW data are within the range of the 2006 and 2008 data, some of the higher concentrations in both Vanderbilt data sets are not represented by the TCLP data, and U.S. EPA (2008c) show similar trends for barium and molybdenum. This suggests that risks for these metals may be underestimated, which is consistent with selenium as a common driver of the damage cases.

- **Impacts of mercury rules (CAIR and CAMR).** While CAIR and CAMR will reduce emissions of mercury and other metals from coal-fired power plants, mercury and other more volatile metals will be transferred from the flue gas to fly ash and other air pollution control residues, including the sludge from wet scrubbers. EPA ORD has research underway to evaluate changes to CCW characteristics and leaching of mercury and other metals from CAIR and CAMR. Data from the first report (U.S. EPA, 2006c) suggest that although total mercury will increase in CCW from the use of sorbents as mercury controls, the leachability of mercury may be reduced. Data from U.S. EPA (2008c) add to this assessment by supporting similar findings.

- **Mercury and nondetect analyses.** Because of a high proportion of nondetect values and a limited number of measurements, the risks from mercury in CCW could not be evaluated for either landfills or surface impoundments and for antimony and thallium in surface impoundments. The 2006 leaching study data suggest that mercury levels are fairly low in fly ash from coal combustion, a conclusion generally confirmed by the 2008 study report (U.S. EPA, 2008c), although that study did find higher mercury leachate concentrations from scrubber sludge than other coal wastes and found that blending fly ash and lime can increase mercury leaching from scrubber sludge.

Uncertainties that are more difficult to evaluate with respect to CCW risk results include the following:

- **Well distance.** Nearest well distances were taken from a survey of MSW landfills, as data were not available from CCW sites. EPA believes that this is a protective assumption because MSW landfills generally tend to be in more populated areas, but there are little data available to test this hypothesis.

- **Liner conditions.** Liner design and performance for CCW WMUs were based on data and assumptions EPA developed to be appropriate for nonhazardous industrial waste landfills. EPA believes that CCW landfills should have similar performance characteristics, but does not have the quantitative data to verify that.

- **Data gaps for ecological receptors.** Insufficient data were available to develop screening levels and quantitative risk estimates for terrestrial amphibians, but EPA acknowledges that damage cases indicate risk to terrestrial amphibian and plant communities through exposure to selenium and boron.

- **Ecosystems and receptors at risk.** Certain critical assessment endpoints were not evaluated in this analysis, including impacts on managed lands, critical habitats, and threatened and endangered species.

- **Synergistic risk.** The impact of exposures of multiple contaminants to human and ecological risks was not evaluated in this analysis. EPA recognizes that a single-constituent analysis may underestimate risks associated with multiple chemical exposures.

These are potentially the more significant uncertainties associated with the CCW risk assessment. Other uncertainties are discussed in **Section 4.4**.

Given the results and characterization above, composite liners, as modeled in this risk assessment, effectively reduce risks from all pathways and constituents to levels below an excess cancer risk of 1 in 100,000 or an HQ of 1 for both landfills and surface impoundments. The CCW risk assessment suggests that the management of CCW in unlined landfills and unlined surface impoundments may present risks to human health and the environment. From the perspective of what is known about toxic effects in humans, arsenic, nitrates, cadmium, and selenium appear to be among the constituents that may present risks of concern depending on the specific waste management practices employed. From the perspective of what is known about toxic effects in ecological receptors, arsenic, boron, lead, and selenium emerge as having documented adverse effects on ecological receptors.

The estimated human health arsenic risks from clay-lined units are lower than the risks of unlined units, but are still above a 1 in 100,000 excess cancer risk or an HQ of 1. In addition, surface impoundments typically showed higher risks than landfills, regardless of liner type. These risk results are largely consistent with damage cases compiled by EPA (U.S. EPA, 2000, 2003e, 2007) and others (Lang and Schlictmann, 2004; Zillmer and Fauble, 2004; Carlson and Adriano, 1993; Rowe et al., 2002; Hopkins et al., 2006). These results suggest that with a higher prevalence of composite liners in new CCW disposal facilities, future national risks from onsite CCW disposal are likely to be lower than those presented in this risk assessment (which is based on 1995 CCW WMUs).

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Appendix A. Constituent Data

The coal combustion waste (CCW) risk assessment addressed metals and inorganic constituents identified by EPA as potential constituents of concern in CCW (**Table A-1**). EPA-derived waste concentrations for these constituents from the CCW constituent database, which includes analyte concentration data in three tables representing different types of waste samples: landfill leachate analyses (in mg/L), surface impoundment and landfill porewater analyses (in mg/L), and analyses of whole waste samples (in mg/kg). Each database table specifies, for most samples, the type of waste sampled and the type of coal burned at the facility.

Table A-1. Constituents Addressed in the CCW Risk Assessment

Constituent	CAS ID	Constituent	CAS ID
Metals		***Inorganic Anions***	
Aluminum	7429-90-5	Chloride	16887-00-6
Antimony	7440-36-0	Cyanide	57-12-5
Arsenic	7440-38-2	Fluoride	16984-48-8
Barium	7440-39-3	Total Nitrate Nitrogen	14797-55-8
Beryllium	7440-41-7	Phosphate	14265-44-2
Boron	7440-42-8	Silicon	7631-86-9
Cadmium	7440-43-9	Sulfate	14808-79-8
Chromium	7440-47-3	Sulfide	18496-25-8
Cobalt	7440-48-4	***Inorganic Cations***	
Copper	7440-50-8	Ammonia	7664-41-7
Iron	7439-89-6	Calcium	7440-70-2
Lead	7439-92-1	pH	12408-02-5
Magnesium	7439-95-4	Potassium	7440-09-7
Manganese	7439-96-5	Sodium	7440-23-5
Mercury	7439-97-6	***Nonmetallic Elements***	
Molybdenum	7439-98-7	Inorganic Carbon	7440-44-0
Nickel	7440-02-0	Total Elemental Sulfur	7704-34-9
Selenium	7782-49-2	***Measurements***	
Silver	7440-22-4	Total Dissolved Solids	none
Strontium	7440-24-6	Total Organic Carbon	none
Thallium	7440-28-0	Dissolved Organic Carbon	none
Vanadium	7440-62-2		
Zinc	7440-66-6		

A.1 Data Sources

EPA prepared the CCW constituent database in 2002. The 2002 CCW constituent database includes all of the waste characterization data used by EPA in its risk assessments in support of the March 1999 *Report to Congress: Wastes from the Combustion of Fossil Fuels* (the RTC) (U.S. EPA, 1999). In addition to the data set from the March 1999 RTC, EPA supplemented the database with the following data:

- Data submitted with public comments to EPA on the 1999 RTC
- Data submitted with public comments to EPA concerning the May 22, 2000, Final Regulatory Determination
- Data collected by and provided to EPA since the end of the public comment period on the Final Regulatory Determination
- Data identified from literature searches.

The primary sources of these additional data include the electric power industry, state and federal regulatory agencies, and scientific literature. **Attachment A-1** is a complete list of the sources of data contained in the 2002 CCW constituent database.

The additional data represent a significant expansion in the quantity of characterization data available to EPA for analysis. For example, the data set used for the risk assessments supporting the RTC covered approximately 50 CCW generation and/or disposal sites. With the addition of the supplemental data, the 2002 CCW constituent database now covers more than 160 sites. The 1999 data set included approximately 10,000 individual samples of CCW. The 2002 CCW constituent database now includes more than 35,000 individual samples.

The additional data also represent an expansion in the scope of characterization data available to EPA for analysis. The 1999 data were obtained exclusively from the electric power industry. As shown in Attachment A-1, the 2002 data set includes data from other sources, such as scientific literature and state and federal regulatory agencies. The 1999 data set included analyses of whole waste samples, surface impoundment and landfill porewater analyses, and analyses of extracts obtained using the Toxicity Characteristic Leaching Procedure (TCLP), the Synthetic Precipitation Leaching Procedure (SPLP), and Extraction Procedure (EP) Toxicity leaching methods. The 2002 data set added analyses of actual landfill leachate (e.g., obtained from leachate collection systems), analyses of extracts obtained using other leaching methods (including higher retention time leaching methods), and porewater analyses.

The 2002 CCW constituent database represents CCW characteristics across a broad cross-section of the generating universe. Not only does the database include data from a large number of sites, but these sites are distributed throughout the United States, as shown in **Table A-2**. The database includes data for all major types of CCW (i.e., fly ash, bottom ash, flue gas desulfurization [FGD] sludge, fluidized bed combustion [FBC] fly ash, and FBC bed ash), from mixtures of CCW types that are commonly created during disposal operations (e.g., combined fly ash and bottom ash), and from CCW mixed with coal refuse (a common disposal practice). **Section A.2** discusses waste types in more detail.

Table A-2. States Included in the CCW Constituent Database

Alaska	Illinois	Maryland
Arkansas	Indiana	Michigan
California	Kentucky	Ohio
Colorado	Missouri	Oklahoma
Connecticut	North Carolina	Pennsylvania
Florida	North Dakota	Tennessee
Georgia	Nebraska	Texas
Hawaii	New Mexico	Wisconsin
Iowa	Louisiana	West Virginia

The database also includes data for CCW generated from combustion of all major coal ranks: bituminous, sub-bituminous, lignite, and anthracite. Although the database does include coal type designations for most of the entries, in many cases the type is not specified. In addition, many coal plants mix coal from different sources (e.g., eastern and western coals), depending on prices and the need to reduce sulfur levels. As a result, correlations of risk results with coal types may be difficult and may not produce significant results.

A.2 Data Preparation

Table A-3 lists the waste types evaluated in the CCW risk assessment, along with the number of sites representing each waste type in the CCW constituent database. Key steps in preparing these data for risk assessment include (1) selection and grouping of waste types to be addressed, (2) selection of the analyte data to be used, and (3) processing of these data to develop the analyte concentrations for the screening analysis and full-scale risk assessment.

Table A-3. Waste Streams in CCW Constituent Database

Waste Type **Waste Streams**	**Number of Sites by Waste Type[a]**		
	Landfill Leachate	**Surface Impoundment Porewater**	**Total Waste**
Conventional Combustion Waste	*97*	*13*	*62*
Ash (not otherwise specified)	43	0	30
Fly ash	61	2	33
Bottom ash & slag	24	3	23
Combined fly & bottom ash	7	4	4
FGD sludge	4	6	5
Codisposed Ash & Coal Refuse	9	5	1
Fluidized Bed Combustion Waste	*58*	*0*	*54*
Ash (not otherwise specified)	18	0	10
Fly ash	33	0	32
Bottom and bed ash	26	0	25
Combined fly & bottom ash	20	0	22

[a] Site counts by waste type from leachate, porewater, and whole waste data tables in the 2002 CCW constituent database.

A.2.1 Selection and Grouping of Waste Types of Concern

The CCW constituent database contains a variety of waste types. Some selection and grouping of these types was appropriate so that the risk assessment could evaluate risks consistently for groups of wastes that are expected to behave similarly when disposed in landfills and surface impoundments.

Combustion ash types in the CCW constituent database include fly ash, bottom ash, bed ash, slag, combined fly and bottom ash, and coal ash not otherwise specified. Based on a statistical analysis that showed no significant difference in leachate and porewater chemistry, the analysis combines data for these ash types for landfills and surface impoundments. FGD sludge was also combined with these conventional combustion ash types based on insignificant differences in porewater chemistry and the fact that FGD sludge is usually codisposed with varying amounts of fly ash and bottom ash.

CCW porewater constituent data did show that FBC wastes and codisposed ash and coal refuse (coal waste from coal crushers and other coal preparation and handling operations[1]) differ significantly from coal combustion ash in their composition and leachate chemistry, so these wastes were addressed separately in the risk analysis. FBC waste chemistry is impacted by the limestone injected with coal in FBC units for sulfur capture and tends to be very alkaline with high levels of calcium and sulfate. Coal refuse is high in pyrite, which generates sulfuric acid when disposed. As a result, combustion wastes exhibit a lower pH when codisposed with coal refuse.

A.2.2 Selection of Appropriate Analyte Data

CCW analyte concentration data represent leachate from landfills and surface impoundments and whole waste in landfills, as follows:

- Whole waste analyte concentrations (in mg/kg) represent landfill waste.
- Analyte concentrations (in mg/L) in porewater sampled from surface impoundment sediments represent surface impoundment leachate.
- Analyte concentrations for extracts from leaching methods, analyses of actual landfill leachate, and landfill porewater analyses represent landfill leachate. Because the CCW constituent database includes analyte concentrations from several leaching methods, a decision hierarchy was used to select leachate analyses to use in the risk assessment (**Table A-4**).

As shown in Table A-4, the methods thought to best represent long-term waste monofill porewater composition (i.e., methods with long equilibration times and low liquid-to-solid ratios) represent only a few sites, with most sites having TCLP and/or SPLP measurements. To best represent CCW landfill waste concentration at a wide variety of sites, the hierarchy rank shown in Table A-4 was used to select the best method for a particular site. For sites where two or more

[1] Coal refuse is the waste coal produced from coal handling, crushing, and sizing operations. In the CCW constituent database, codisposed coal refuse includes “combined ash and coal gob”, “combined ash and coal refuse”, and “combined bottom ash and pyrites”.

methods were available in the same rank (which often occurs for SPLP and TCLP analyses), the screening analysis used the method with the highest analyte concentrations. This ensured that the data used in the risk assessment were the best that were available and represent a broad variety of waste disposal conditions.

Table A-4. Comparison/Hierarchy of Leaching Methods for Landfills Represented in CCW Constituent Database

Method (Rank)	Description	Advantages	Disadvantages
Landfill leachate (1)	Direct samples of landfill leachate	Most representative of leachate chemistry	Low number of sites represented
Landfill porewater (1)	Direct porewater samples from landfill	Most representative of leachate chemistry	Low number of sites represented
High retention time and low liquid-to-solid ratio (L:S) methods (2)	Waste extractions with long equilibration times (days to weeks) and low L:S	Better representation of landfill equilibration times and L:S	Low number of sites represented
Low L:S methods (3)	Waste extractions with low L:S	Better representation of landfill L:S	Low number of sites represented; equilibrium times relatively short
High retention time methods (3)	Waste extractions with long equilibration times (days to weeks)	Better representation of landfill equilibration times	Low number of sites represented; L:S relatively high
TCLP (4)	Toxicity Characteristic Leaching Procedure waste extractions	Most representative in terms of number of sites, waste types covered	High L:S (20:1) can dilute leachate concentrations; short equilibration time (18 hours) may not allow equilibrium to develop; Na-acetate buffer can overestimate leaching for some constituents (e.g., Pb)
SPLP (4)	Synthetic Precipitation Leaching Procedure and other dilute water waste extractions	More representative in terms of number of sites, waste types covered; extract similar to precipitation	High L:S (20:1) can dilute leachate concentrations; short equilibration time (18 hours) may not allow equilibrium to develop

A.2.3 Development of Waste Constituent Concentrations

To allow risk assessment results to be organized by waste constituent and waste type, CCW data were processed to produce a single concentration per waste stream (surface impoundment porewater, landfill leachate, and landfill whole waste), analyte, and site for use in the risk assessment. Data processing to prepare these analyte concentrations for the CCW risk assessment involved two steps:

1. **Calculation of average constituent concentrations by site for landfill leachate, surface impoundment porewater, and total ash concentrations.** Site averaging avoids potential bias toward sites with many analyses per analyte. During site averaging, any separate waste disposal scenarios occurring at a site (e.g., non-FBC and FBC ash) were treated as separate “sites” and were averaged independently. This approach is consistent with that used in the 1998 CCW risk analysis. As in 1998, nondetects were averaged at one-half the reported detection limit.

2. **Selection of waste concentrations from site-averaged values.** For the Monte Carlo analysis, the analysis randomly selected, by waste type/waste management unit (WMU) scenario, site-averaged leachate concentrations. For landfills, a corresponding total waste analysis was pulled from the database or calculated from a constituent-specific relationship between landfill leachate and total waste analyses.

A.3 Results

Attachment A-2 provides the site-averaged constituent data used (sampled) in the full-scale CCW risk assessment by waste type/WMU scenario. **Attachment A-3** presents summary statistics, by constituent and WMU type, including the 90th percentile waste concentrations used in the screening analysis. Attachment A-3 also includes figures (**Figures A-3-1** to **A-3-3**) that illustrate the differences between site-averaged and non-site-averaged waste concentrations for surface impoundment porewater (Figure A-3-1), landfill leachate (Figure A-3-2), and total waste analyses (Figure A-3-3).

A.4 References

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Attachment A-1: Sources of Data

General

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Attachment A-2: CCW Constituent Data

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
11 - FBC	LF	Arsenic	0.002916667	3	3	51
11 - FBC	LF	Barium	0.339166667	3	3	174.5
11 - FBC	LF	Cadmium	0.0005	4	4	6.91875
11 - FBC	LF	Lead	0.0025	4	4	39.5
11 - FBC	LF	Mercury	0.00125	4	4	0.1325
11 - FBC	LF	Selenium	0.00225	4	2	45.5
12 - FBC	LF	Aluminum	3.4	1	0	35874.6
12 - FBC	LF	Antimony	0.27	1	0	18
12 - FBC	LF	Arsenic	0.02205	2	0	57.64333333
12 - FBC	LF	Barium	0.196	2	1	203.805
12 - FBC	LF	Boron	0.05	1	1	20.324
12 - FBC	LF	Cadmium	0.005625	2	1	0.279375
12 - FBC	LF	Lead	0.025	1	1	45.66666667
12 - FBC	LF	Mercury	0.00005	2	2	1.2575
12 - FBC	LF	Molybdenum	0.21	1	0	15.5
12 - FBC	LF	Selenium	0.04355	2	0	7.365833333
17 - FBC	LF	Aluminum	4.788	5	0	46194.8
17 - FBC	LF	Antimony	0.0708	5	2	14.60333333
17 - FBC	LF	Arsenic	0.1378	5	0	71.46666667
17 - FBC	LF	Barium	0.3512	5	1	134.975
17 - FBC	LF	Boron	0.4404	5	1	34.06333333
17 - FBC	LF	Cadmium	0.0434	5	2	3.058333333
17 - FBC	LF	Lead	0.2372	5	2	49.65
17 - FBC	LF	Mercury	0.01022	5	5	1.60345
17 - FBC	LF	Molybdenum	0.097	5	1	3.515
17 - FBC	LF	Selenium	0.06315	5	2	3.301666667
18 - FBC	LF	Aluminum	1.333333333	3	0	23501.33333
18 - FBC	LF	Antimony	0.025	3	3	5
18 - FBC	LF	Arsenic	0.025	3	3	53.33333333
18 - FBC	LF	Barium	0.175	3	1	211.3333333
18 - FBC	LF	Boron	1.341666667	3	1	532.3333333
18 - FBC	LF	Cadmium	0.025	3	3	2.5
18 - FBC	LF	Cobalt	0.025	3	3	11
18 - FBC	LF	Lead	0.025	3	3	22
18 - FBC	LF	Mercury	0.0005	3	2	0.268333333
18 - FBC	LF	Molybdenum	0.175	3	1	7.666666667

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
18 – FBC	LF	Selenium	0.108333333	3	1	0.5
18 - FBC	LF	Thallium	0.025	3	3	1
19 - FBC	LF	Arsenic	0.0875	2	1	6.25
19 - FBC	LF	Barium	0.27	2	1	39.2
19 - FBC	LF	Cadmium	0.01375	2	2	2.5
19 - FBC	LF	Lead	0.0675	2	2	3.75
19 - FBC	LF	Mercury	0.00125	2	1	0.125
19 - FBC	LF	Selenium	0.06875	2	2	6.25
20 - FBC	LF	Aluminum	10.81	12	0	34329.16522
20 - FBC	LF	Antimony	0.787	10	0	46.28125
20 - FBC	LF	Arsenic	0.035	12	0	15.03130435
20 - FBC	LF	Barium	0.381818182	11	0	255.4608696
20 - FBC	LF	Boron	0.457142857	7	0	28.0025
20 - FBC	LF	Cadmium	0.03625	8	0	2.089166667
20 - FBC	LF	Lead	0.301111111	9	0	36.20052632
20 - FBC	LF	Mercury	0.29	1	0	0.454
20 - FBC	LF	Molybdenum	0.392857143	7	0	12.10111111
20 - FBC	LF	Selenium	0.088571429	7	0	4.177333333
21 - FBC	LF	Aluminum	1.91	3	0	14677.33167
21 - FBC	LF	Antimony	0.001833333	3	3	1.083333333
21 - FBC	LF	Arsenic	0.012	3	0	10.76666667
21 - FBC	LF	Barium	0.022333333	3	2	176.2666667
21 - FBC	LF	Boron	0.036666667	3	2	14.38333333
21 - FBC	LF	Cadmium	0.002083333	3	3	0.145833333
21 - FBC	LF	Cobalt	0.008333333	3	2	5.756666667
21 - FBC	LF	Lead	0.009166667	3	3	27.3
21 - FBC	LF	Mercury	0.000133333	3	2	0.431666667
21 - FBC	LF	Molybdenum	0.0125	3	3	3.708333333
21 - FBC	LF	Selenium	0.016666667	3	0	10.9
2-18 - Ash	LF	Arsenic	0.41794375	16	3	
2-18 - Ash	LF	Barium	0.4305625	16	0	
2-18 - Ash	LF	Boron	1.0160625	16	0	
2-18 - Ash	LF	Cadmium	0.05825	16	11	
2-18 - Ash	LF	Lead	0.2819375	16	11	
2-18 - Ash	LF	Mercury	0.000115625	16	16	
2-18 - Ash	LF	Selenium	0.01534375	16	8	
22 - FBC	LF	Arsenic	0.055	5	3	
22 - FBC	LF	Barium	0.5405	5	1	
22 - FBC	LF	Cadmium	0.003	5	5	
22 - FBC	LF	Lead	0.015	5	5	
22 - FBC	LF	Mercury	0.0002	5	3	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
22 - FBC	LF	Molybdenum	0.0125	2	2	

(continued)

22 - FBC	LF	Selenium	0.032	5	5	
23 - FBC	LF	Barium	0.81	4	0	
25 - FBC	LF	Arsenic	0.125	1	1	
25 - FBC	LF	Barium	2.5	1	1	
25 - FBC	LF	Cadmium	0.025	1	1	
25 - FBC	LF	Lead	0.125	1	1	
25 - FBC	LF	Mercury	0.005	1	1	
25 - FBC	LF	Selenium	0.025	1	1	
28 - FBC	LF	Barium	2.525	2	0	235.11875
30 - FBC	LF	Aluminum	6.894555556	18	7	28246.46923
30 - FBC	LF	Antimony	0.548082353	17	2	61.49315385
30 - FBC	LF	Arsenic	0.050694444	18	3	48.55980769
30 - FBC	LF	Barium	0.286388889	18	6	120.0687692
30 - FBC	LF	Boron	0.31759375	16	7	30.83913462
30 - FBC	LF	Cadmium	0.023125	14	3	1.916230769
30 - FBC	LF	Lead	0.240805556	18	4	39.36092308
30 - FBC	LF	Mercury	0.000744444	18	17	10.91689923
30 - FBC	LF	Molybdenum	0.138125	16	10	14.50257692
30 - FBC	LF	Selenium	0.10475	16	10	5.603596154
31 - FBC	LF	Aluminum	0.28	1	0	29437.5
31 - FBC	LF	Antimony	0.00065	1	1	5.0325
31 - FBC	LF	Arsenic	0.0687	4	2	26.825
31 - FBC	LF	Barium	0.58275	4	0	170.25
31 - FBC	LF	Boron	26.7	1	0	930
31 - FBC	LF	Cadmium	0.02775	4	3	5.45
31 - FBC	LF	Cobalt	0.0065	1	0	6.42
31 - FBC	LF	Lead	0.03025	4	3	1.19
31 - FBC	LF	Mercury	0.00095	4	1	0.61
31 - FBC	LF	Molybdenum	0.085	1	0	8
31 - FBC	LF	Selenium	0.06485	4	2	7.54
32 - FBC	LF	Arsenic	0.35	1	1	1.4
32 - FBC	LF	Barium	0.085	1	0	
32 - FBC	LF	Cadmium	0.005	1	1	0.009
32 - FBC	LF	Lead	0.05	1	1	0.45
32 - FBC	LF	Mercury	0.0001	1	1	0.03
32 - FBC	LF	Selenium	0.175	1	1	3.5
33 - FBC	LF	Arsenic	0.015	1	1	
33 - FBC	LF	Barium	42	1	0	
33 - FBC	LF	Boron	0.06	1	0	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
33 - FBC	LF	Cadmium	0.00125	1	1	
33 - FBC	LF	Cobalt	0.0025	1	1	
33 - FBC	LF	Mercury	0.00005	1	1	
33 - FBC	LF	Selenium	0.01	1	1	
35 - FBC	LF	Arsenic	0.015	1	1	
35 - FBC	LF	Barium	2.6	1	0	
35 - FBC	LF	Cadmium	0.009	1	0	
35 - FBC	LF	Lead	0.035	1	1	
35 - FBC	LF	Mercury	0.00025	1	1	
35 - FBC	LF	Selenium	0.2	1	0	
37 - FBC	LF	Arsenic	0.011102941	17	9	5.79
37 - FBC	LF	Barium	2.104705882	17	2	
37 - FBC	LF	Boron	1.125	5	1	15.9
37 - FBC	LF	Cadmium	0.046176471	17	4	4.183333333
37 - FBC	LF	Cobalt	0.246	5	0	
37 - FBC	LF	Lead	0.287352941	17	6	55
37 - FBC	LF	Mercury	0.001314706	17	4	0.01125
37 - FBC	LF	Selenium	0.01075	17	9	3.42
38 - FBC	LF	Aluminum	2.256666667	9	2	26711.25
38 - FBC	LF	Antimony	0.213069444	9	6	11.27770833
38 - FBC	LF	Arsenic	0.024554444	9	3	25.136075
38 - FBC	LF	Barium	0.178888889	9	4	181.0083333
38 - FBC	LF	Boron	0.346555556	9	2	26.98916667
38 - FBC	LF	Cadmium	0.007388889	9	5	0.71625
38 - FBC	LF	Cobalt	0.008566667	3	2	4.515
38 - FBC	LF	Lead	0.0565	9	6	28.54166667
38 - FBC	LF	Mercury	0.000344444	9	8	0.18195
38 - FBC	LF	Molybdenum	0.177375	8	2	14.1875
38 - FBC	LF	Selenium	0.088561111	9	4	7.682450833
39 - FBC	LF	Arsenic	0.075	1	1	14.5
39 - FBC	LF	Barium	0.395	2	1	590
39 - FBC	LF	Boron	0.76	1	0	
39 - FBC	LF	Cadmium	0.005	1	1	0.5
39 - FBC	LF	Lead	0.025	1	1	15
39 - FBC	LF	Mercury	0.00025	1	1	0.17
39 - FBC	LF	Molybdenum	0.14	1	0	13.5
39 - FBC	LF	Selenium	0.025	1	1	21.5
4 - FBC	LF	Aluminum	13.556	5	0	16084.68429
4 - FBC	LF	Antimony	0.2236	5	2	26.78817857
4 - FBC	LF	Arsenic	0.271	5	0	28.03585714
4 - FBC	LF	Barium	0.6346	5	1	154.95

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
4 - FBC	LF	Boron	0.693	4	0	13.026
4 - FBC	LF	Cadmium	0.0115	5	2	0.646539286
4 - FBC	LF	Mercury	0.00005	5	5	0.087192857
4 - FBC	LF	Lead	0.1834	5	1	18.35671429
4 - FBC	LF	Molybdenum	0.286666667	3	0	16.18257143
4 - FBC	LF	Selenium	0.0620625	4	2	1.505421429
41 - FBC	LF	Antimony	0.025	5	5	1.551333333
41 - FBC	LF	Arsenic	0.035471698	53	50	13.72255319
41 - FBC	LF	Barium	0.095694444	54	25	19.05490196
41 - FBC	LF	Cadmium	0.022355769	52	51	0.427826087
41 - FBC	LF	Lead	0.017548077	52	51	0.935208333
41 - FBC	LF	Mercury	0.000596154	52	50	0.119542553
41 - FBC	LF	Selenium	0.024433962	53	51	1.505744681
41 - FBC	LF	Thallium	0.031	5	4	3.662790698
42 - FBC	LF	Arsenic	0.0125	2	2	
42 - FBC	LF	Barium	0.1625	2	1	
42 - FBC	LF	Cadmium	0.005	2	2	
42 - FBC	LF	Lead	0.0075	2	2	
42 - FBC	LF	Mercury	0.0005	2	2	
42 - FBC	LF	Selenium	0.0125	2	2	
43 - FBC	LF	Arsenic	0.0125	2	2	
43 - FBC	LF	Barium	0.0875	2	1	
43 - FBC	LF	Cadmium	0.005	2	2	
43 - FBC	LF	Lead	0.0075	2	2	
43 - FBC	LF	Mercury	0.0005	2	2	
43 - FBC	LF	Selenium	0.08625	2	1	
6 - FBC	LF	Aluminum	0.1525	2	1	42736.5
6 - FBC	LF	Antimony	0.05	2	2	16.25
6 - FBC	LF	Arsenic	0.09125	2	1	126.6
6 - FBC	LF	Barium	0.285	2	0	221.5
6 - FBC	LF	Boron	0.1425	2	1	73.8
6 - FBC	LF	Cadmium	0.0025	2	2	1.29625
6 - FBC	LF	Lead	0.01375	2	2	8.1125
6 - FBC	LF	Mercury	0.00005	2	2	1.16
6 - FBC	LF	Molybdenum	0.09	2	0	1.425
6 - FBC	LF	Selenium	0.1025	2	1	84.5625
Amerikohl - FBC	LF	Aluminum	0.753333333	3	0	51600
Amerikohl - FBC	LF	Antimony	0.345	3	3	20
Amerikohl - FBC	LF	Arsenic	0.024166667	3	3	114
Amerikohl - FBC	LF	Barium	0.1	3	3	140
Amerikohl - FBC	LF	Boron	0.346666667	3	1	60

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Amerikohl - FBC	LF	Cadmium	0.004166667	3	3	0.15
Amerikohl - FBC	LF	Cobalt	0.175	3	3	30
Amerikohl - FBC	LF	Lead	0.009166667	3	3	23
Amerikohl - FBC	LF	Mercury	0.0005	3	3	0.15
Amerikohl - FBC	LF	Molybdenum	0.266666667	3	1	10
Amerikohl - FBC	LF	Nitrate/Nitrite	3.15	3	3	
Amerikohl - FBC	LF	Selenium	0.044166667	3	3	3.5
Arkwright - Ash	LF	Arsenic	0.07	1	0	
Arkwright - Ash	LF	Barium	0.4	1	0	
Arkwright - Ash	LF	Cadmium	0.01	1	0	
Arkwright - Ash	LF	Lead	0.04	1	0	
Arkwright - Ash	LF	Selenium	0.02	1	0	
Barry - Ash	LF	Arsenic	1	1	0	
Barry - Ash	LF	Barium	0.7	1	0	
Barry - Ash	LF	Cadmium	0.005	1	0	
Barry - Ash	LF	Lead	0.04	1	0	
Barry - Ash	LF	Selenium	0.07	1	0	
Belle Ayr - Ash	LF	Aluminum	0.036666667	3	0	
Belle Ayr - Ash	LF	Antimony	0.021	2	0	
Belle Ayr - Ash	LF	Arsenic	0.181	3	0	
Belle Ayr - Ash	LF	Barium	1.163333333	3	0	
Belle Ayr - Ash	LF	Cobalt	0.0075	2	0	
Belle Ayr - Ash	LF	Molybdenum	0.325	3	0	
Belle Ayr - Ash	LF	Selenium	0.652333333	3	0	
Big Gorilla Pit - FBC	LF	Aluminum	3.774166667	12	0	18440.58824
Big Gorilla Pit - FBC	LF	Antimony	0.037166667	12	1	1.244485294
Big Gorilla Pit - FBC	LF	Arsenic	0.023181818	22	21	7.534117647
Big Gorilla Pit - FBC	LF	Barium	0.243636364	11	3	147.7320588
Big Gorilla Pit - FBC	LF	Boron	0.677916667	12	2	29.64058824
Big Gorilla Pit - FBC	LF	Cadmium	0.015227273	22	22	0.58728125
Big Gorilla Pit - FBC	LF	Cobalt	0.008553571	14	11	2.374214286
Big Gorilla Pit - FBC	LF	Lead	0.08125	12	7	19.51823529
Big Gorilla Pit - FBC	LF	Mercury	0.001704545	22	19	0.302990909
Big Gorilla Pit - FBC	LF	Molybdenum	0.1202	10	1	6.429333333
Big Gorilla Pit - FBC	LF	Nitrate/Nitrite	1.755857143	14	3	
Big Gorilla Pit - FBC	LF	Selenium	0.10975	12	1	7.159397059
Bowen - Ash	LF	Arsenic	0.6	1	0	68
Bowen - Ash	LF	Barium	0.3	1	0	974
Bowen - Ash	LF	Cadmium	0.01	1	0	0.7
Bowen - Ash	LF	Lead	0.04	1	0	63.9
Bowen - Ash	LF	Selenium	0.1	1	0	

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CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Branch - Ash	LF	Arsenic	0.04	1	0	
Branch - Ash	LF	Barium	0.5	1	0	
Branch - Ash	LF	Cadmium	0.01	1	0	
Branch - Ash	LF	Lead	0.04	1	0	
Branch - Ash	LF	Selenium	0.06	1	0	
Buckheart Mine - Ash	LF	Antimony	0.01854	40	14	
Buckheart Mine - Ash	LF	Arsenic	0.122357143	42	13	
Buckheart Mine - Ash	LF	Barium	0.364809524	42	0	
Buckheart Mine - Ash	LF	Boron	9.998738095	42	0	
Buckheart Mine - Ash	LF	Cadmium	0.0235	42	8	
Buckheart Mine - Ash	LF	Cobalt	0.048047619	42	17	
Buckheart Mine - Ash	LF	Lead	0.27887619	42	9	
Buckheart Mine - Ash	LF	Mercury	0.000107143	42	40	
Buckheart Mine - Ash	LF	Selenium	0.118266667	42	26	
Buckheart Mine - Ash	LF	Thallium	0.017875	40	10	
Buckheart Mine - FBC	LF	Antimony	0.0018125	8	8	
Buckheart Mine - FBC	LF	Arsenic	0.0465	8	5	
Buckheart Mine - FBC	LF	Barium	0.560125	8	1	
Buckheart Mine - FBC	LF	Boron	3.157	8	0	
Buckheart Mine - FBC	LF	Cadmium	0.0033125	8	7	
Buckheart Mine - FBC	LF	Cobalt	0.02875	8	7	
Buckheart Mine - FBC	LF	Lead	0.036	8	4	
Buckheart Mine - FBC	LF	Mercury	0.0005	8	4	
Buckheart Mine - FBC	LF	Selenium	0.050625	8	5	
Buckheart Mine - FBC	LF	Thallium	0.001	8	8	
CAER - Ash	LF	Arsenic	1.132	5	0	77.32222222
CAER - Ash	LF	Barium	0.315	5	0	537.6666667
CAER - Ash	LF	Cadmium	0.0942	5	0	
CAER - Ash	LF	Lead	0.1	5	2	73.62375
CAER - Ash	LF	Mercury	0.00025	5	5	
CAER - Ash	LF	Selenium	0.103	5	0	
Canton Site - Ash	LF	Aluminum	9.818127778	36	0	
Canton Site - Ash	LF	Arsenic	0.0025	2	2	
Canton Site - Ash	LF	Barium	3.0156	10	0	
Canton Site - Ash	LF	Boron	18.62468571	35	0	
Canton Site - Ash	LF	Cadmium	0.0005	2	2	
Canton Site - Ash	LF	Cobalt	0.02	1	1	
Canton Site - Ash	LF	Lead	0.1865	2	0	
Canton Site - Ash	LF	Mercury	0.0001	1	1	
Canton Site - Ash	LF	Molybdenum	30.9359	20	0	
Canton Site - Ash	LF	Nitrate/Nitrite	0.095	1	0	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Canton Site - Ash	LF	Selenium	0.0374	1	0	
Canton Site - FBC	LF	Aluminum	2.461866667	24	0	
Canton Site - FBC	LF	Arsenic	0.005	1	1	
Canton Site - FBC	LF	Barium	0.02	1	0	
Canton Site - FBC	LF	Boron	1.5602625	16	0	
Canton Site - FBC	LF	Cadmium	0.066	1	0	
Canton Site - FBC	LF	Lead	0.062	1	0	
Canton Site – FBC	LF	Mercury	0.0005	1	1	
Canton Site – FBC	LF	Molybdenum	1.768009524	21	0	
Canton Site – FBC	LF	Selenium	0.005	1	1	
Central Cleaning Plant - Ash	LF	Antimony	0.008205882	17	17	
Central Cleaning Plant - Ash	LF	Arsenic	0.005	17	17	
Central Cleaning Plant - Ash	LF	Barium	0.168164706	17	0	
Central Cleaning Plant - Ash	LF	Boron	7.213823529	17	0	
Central Cleaning Plant - Ash	LF	Cadmium	0.004117647	17	16	
Central Cleaning Plant - Ash	LF	Cobalt	0.019588235	17	15	
Central Cleaning Plant - Ash	LF	Lead	0.022782353	17	11	
Central Cleaning Plant - Ash	LF	Mercury	0.000568824	17	11	
Central Cleaning Plant - Ash	LF	Selenium	0.040211765	17	0	
Central Cleaning Plant - Ash	LF	Thallium	0.005	17	17	
CL - Ash and Coal Refuse	LF	Aluminum	2.58	3	0	
CL - Ash and Coal Refuse	LF	Antimony	0.0041	3	0	
CL - Ash and Coal Refuse	LF	Arsenic	0.121266667	3	0	
CL - Ash and Coal Refuse	LF	Barium	3.63	3	0	
CL - Ash and Coal Refuse	LF	Boron	0.103133333	3	0	
CL - Ash and Coal Refuse	LF	Cadmium	0.001	3	0	
CL - Ash and Coal Refuse	LF	Cobalt	0.006066667	3	1	
CL - Ash and Coal Refuse	LF	Lead	0.003533333	3	0	
CL - Ash and Coal Refuse	LF	Mercury	0.00005	6	6	
CL - Ash and Coal Refuse	LF	Selenium	0.0452	3	0	
CL - Ash and Coal Refuse	LF	Thallium	0.003483333	3	1	
Coal Creek - Ash	LF	Arsenic	0.0109	2	0	0.086
Coal Creek - Ash	LF	Barium	0.6105	2	0	4.76
Coal Creek - Ash	LF	Boron	6.22	2	0	1.1105
Coal Creek - Ash	LF	Cadmium	0.00015	2	2	0.00045
Coal Creek - Ash	LF	Lead	0.001	2	2	0.02025
Coal Creek - Ash	LF	Mercury	0.000005	2	2	0.0006
Coal Creek - Ash	LF	Selenium	0.0555	2	1	0.00505
Colver Site - FBC	LF	Aluminum	0.248333333	6	1	78878.83333
Colver Site - FBC	LF	Antimony	0.196666667	6	2	166.5
Colver Site - FBC	LF	Arsenic	0.0875	6	1	124.2

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Colver Site - FBC	LF	Barium	0.291666667	6	0	443.8333333
Colver Site - FBC	LF	Boron	0.261666667	6	1	62.6
Colver Site - FBC	LF	Cadmium	0.016666667	6	2	9.994166667
Colver Site - FBC	LF	Lead	0.190833333	6	2	192.075
Colver Site - FBC	LF	Mercury	0.00015	6	5	0.586666667
Colver Site - FBC	LF	Molybdenum	0.143333333	6	0	30.65833333
Colver Site - FBC	LF	Selenium	0.48	6	1	68.70833333
Conemaugh - Ash	LF	Aluminum	1.245	2	0	
Conemaugh - Ash	LF	Antimony	0.075	1	1	
Conemaugh - Ash	LF	Arsenic	0.388333333	3	1	
Conemaugh - Ash	LF	Barium	0.331666667	3	0	
Conemaugh - Ash	LF	Boron	0.91	1	0	
Conemaugh - Ash	LF	Cadmium	0.01	3	0	
Conemaugh - Ash	LF	Cobalt	0.026	1	0	
Conemaugh - Ash	LF	Lead	0.1	2	2	
Conemaugh - Ash	LF	Mercury	0.00055	2	2	
Conemaugh - Ash	LF	Molybdenum	0.355	2	0	
Conemaugh - Ash	LF	Selenium	0.295	2	1	
Conemaugh - Ash	LF	Thallium	0.024	1	0	
Conemaugh - Ash and Coal Refuse	LF	Aluminum	1.467666667	3	0	
Conemaugh - Ash and Coal Refuse	LF	Antimony	0.075	3	3	
Conemaugh - Ash and Coal Refuse	LF	Arsenic	0.625	2	2	
Conemaugh - Ash and Coal Refuse	LF	Barium	0.145666667	3	0	
Conemaugh - Ash and Coal Refuse	LF	Boron	0.095	2	0	
Conemaugh - Ash and Coal Refuse	LF	Cadmium	0.002	3	3	
Conemaugh - Ash and Coal Refuse	LF	Cobalt	0.009	1	0	
Conemaugh - Ash and Coal Refuse	LF	Lead	0.073333333	3	2	
Conemaugh - Ash and Coal Refuse	LF	Mercury	0.0004	3	2	
Conemaugh - Ash and Coal Refuse	LF	Molybdenum	0.01	1	0	
Conemaugh - Ash and Coal Refuse	LF	Selenium	0.179833333	3	1	
Conemaugh - Ash and Coal Refuse	LF	Thallium	0.005	1	0	
Crist - Ash	LF	Arsenic	0.02	1	0	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Crist - Ash	LF	Barium	0.1	1	0	
Crist - Ash	LF	Cadmium	0.02	1	0	
Crist - Ash	LF	Lead	0.003	1	0	
Crist - Ash	LF	Selenium	0.05	1	0	
Crown III - Ash	LF	Antimony	0.071159259	54	10	
Crown III - Ash	LF	Arsenic	0.352503226	62	29	
Crown III - Ash	LF	Barium	0.279112903	62	3	
Crown III - Ash	LF	Boron	22.93277419	62	0	
Crown III - Ash	LF	Cadmium	0.128258065	62	3	
Crown III - Ash	LF	Cobalt	0.101225806	62	17	
Crown III - Ash	LF	Lead	0.605616935	62	19	
Crown III - Ash	LF	Mercury	0.000104839	62	61	
Crown III - Ash	LF	Molybdenum	0.588888889	9	4	
Crown III - Ash	LF	Selenium	0.03946129	62	46	
Crown III - Ash	LF	Thallium	0.0645	54	18	
Crown III - FBC	LF	Antimony	0.0135	17	9	
Crown III - FBC	LF	Arsenic	0.034822581	31	26	3.766666667
Crown III - FBC	LF	Barium	0.346774194	31	2	150
Crown III - FBC	LF	Boron	2.815296296	27	1	
Crown III - FBC	LF	Cadmium	0.011241935	31	22	2.17
Crown III - FBC	LF	Cobalt	0.02475	24	16	
Crown III - FBC	LF	Lead	0.068645161	31	17	8.233333333
Crown III - FBC	LF	Mercury	0.000164516	31	27	0.381
Crown III - FBC	LF	Molybdenum	0.1522	10	2	
Crown III - FBC	LF	Selenium	0.061467742	31	27	3.3
Crown III - FBC	LF	Thallium	0.004941176	17	11	
CTL-V - Ash	LF	Antimony	0.26	1	0	
CTL-V - Ash	LF	Arsenic	0.037	1	0	
CTL-V - Ash	LF	Barium	0.247	1	0	
CTL-V - Ash	LF	Cadmium	0.04	1	0	
CTL-V - Ash	LF	Lead	0.072	1	0	
CTL-V - Ash	LF	Mercury	0.001	1	0	
CTL-V - Ash	LF	Selenium	0.014	1	0	
CTL-V - Ash	LF	Thallium	0.01	1	0	
CY - Ash	LF	Aluminum	4.735	2	0	
CY - Ash	LF	Antimony	0.0078	2	0	
CY - Ash	LF	Arsenic	0.04825	2	0	
CY - Ash	LF	Barium	1.2395	2	0	
CY - Ash	LF	Boron	6.13	2	0	
CY - Ash	LF	Cadmium	0.0002075	2	1	
CY - Ash	LF	Cobalt	0.001915	4	4	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
CY - Ash	LF	Lead	0.003555	2	1	
CY - Ash	LF	Mercury	0.000265	2	0	
CY - Ash	LF	Selenium	0.004825	2	1	
CY - Ash	LF	Thallium	0.00196	4	4	
Dairyland Power Coop - Ash	LF	Arsenic	0.0328625	8	0	
Dairyland Power Coop - Ash	LF	Barium	0.058740741	27	0	
Dairyland Power Coop - Ash	LF	Boron	68.03979592	49	0	
Dairyland Power Coop - Ash	LF	Cadmium	0.00539	34	0	
Dairyland Power Coop - Ash	LF	Lead	0.0046	7	2	
Dairyland Power Coop - Ash	LF	Mercury	0.000223	2	1	
Dairyland Power Coop - Ash	LF	Selenium	0.0696375	8	0	
Daniel - Ash	LF	Arsenic	0.2	1	0	
Daniel - Ash	LF	Barium	0.4	1	0	
Daniel - Ash	LF	Cadmium	0.001	1	1	
Daniel - Ash	LF	Lead	0.001	1	1	
Daniel - Ash	LF	Selenium	0.001	1	1	
Deer Ridge Mine - Ash	LF	Aluminum	0.5941	10	1	64681.487
Deer Ridge Mine - Ash	LF	Arsenic	0.0029	10	6	21.29419
Deer Ridge Mine - Ash	LF	Barium	0.1448	10	2	258.468
Deer Ridge Mine - Ash	LF	Boron	1.228	10	2	179.354
Deer Ridge Mine - Ash	LF	Cadmium	0.01365	10	1	0.94425
Deer Ridge Mine - Ash	LF	Lead	0.0253	10	2	58.48
Deer Ridge Mine - Ash	LF	Mercury	0.00011025	10	10	0.1158
Deer Ridge Mine - Ash	LF	Molybdenum	0.0756	10	4	6.6287
Deer Ridge Mine - Ash	LF	Nitrate/Nitrite	0.095	3	2	
Deer Ridge Mine - Ash	LF	Selenium	0.01022	10	2	13.1061
DPC - Ash	LF	Antimony	0.04	2	1	0.475
DPC - Ash	LF	Arsenic	0.051	2	0	55.085
DPC - Ash	LF	Barium	0.28	2	0	37.7
DPC - Ash	LF	Boron	27.945	2	0	404.05
DPC - Ash	LF	Cadmium	0.005	4	4	0.56
DPC - Ash	LF	Lead	0.025	4	4	28.7
DPC - Ash	LF	Mercury	0.001	2	2	0.127
DPC - Ash	LF	Nitrate/Nitrite	2.5	2	0	0.2425
DPC - Ash	LF	Selenium	0.046	2	0	3.4445
EERC - Ash	LF	Mercury	0.000025	4	4	
Elkhart Mine - Ash	LF	Antimony	0.025192308	52	46	
Elkhart Mine - Ash	LF	Arsenic	0.043571429	77	71	
Elkhart Mine - Ash	LF	Barium	0.495324675	77	23	
Elkhart Mine - Ash	LF	Boron	6.88961039	77	0	
Elkhart Mine - Ash	LF	Cadmium	0.022551948	77	41	

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CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Elkhart Mine - Ash	LF	Cobalt	0.012785714	77	57	
Elkhart Mine - Ash	LF	Lead	0.027987013	77	66	
Elkhart Mine - Ash	LF	Mercury	0.000148052	77	68	
Elkhart Mine - Ash	LF	Selenium	0.036649351	77	64	
Elkhart Mine - Ash	LF	Thallium	0.015942308	52	48	
Elkhart Mine - FBC	LF	Antimony	0.021875	16	15	
Elkhart Mine - FBC	LF	Arsenic	0.034512195	41	37	
Elkhart Mine - FBC	LF	Barium	0.525365854	41	5	
Elkhart Mine - FBC	LF	Boron	13.13829268	41	0	
Elkhart Mine - FBC	LF	Cadmium	0.003536585	41	41	
Elkhart Mine - FBC	LF	Cobalt	0.007219512	41	39	
Elkhart Mine - FBC	LF	Lead	0.017195122	41	34	
Elkhart Mine - FBC	LF	Mercury	0.000104878	41	40	
Elkhart Mine - FBC	LF	Selenium	0.035365854	41	33	
Elkhart Mine - FBC	LF	Thallium	0.02390625	16	15	
FBX - Ash	LF	Arsenic	0.0025	2	2	
FBX - Ash	LF	Barium	29.6225	2	1	
FBX - Ash	LF	Cadmium	0.2	2	2	
FBX - Ash	LF	Lead	0.5	2	2	
FBX - Ash	LF	Mercury	0.00025	2	2	
FBX - Ash	LF	Selenium	0.01375	2	2	
FC - Ash and Coal Refuse	LF	Aluminum	13.8	2	0	
FC - Ash and Coal Refuse	LF	Antimony	0.00105	4	4	
FC - Ash and Coal Refuse	LF	Arsenic	0.005	2	0	
FC - Ash and Coal Refuse	LF	Barium	0.602	2	0	
FC - Ash and Coal Refuse	LF	Boron	2.54	2	0	
FC - Ash and Coal Refuse	LF	Cadmium	0.00015	4	4	
FC - Ash and Coal Refuse	LF	Cobalt	0.0029	2	0	
FC - Ash and Coal Refuse	LF	Lead	0.00345	2	0	
FC - Ash and Coal Refuse	LF	Mercury	0.00005	4	4	
FC - Ash and Coal Refuse	LF	Selenium	0.01765	2	0	
FC - Ash and Coal Refuse	LF	Thallium	0.00185	4	4	
Florence Mine - Ash	LF	Aluminum	0.03	1	0	
Florence Mine - Ash	LF	Antimony	0.005	1	1	
Florence Mine - Ash	LF	Arsenic	0.07	1	0	
Florence Mine - Ash	LF	Barium	2.23	1	0	
Florence Mine - Ash	LF	Boron	0.01	1	1	
Florence Mine - Ash	LF	Cadmium	0.01	1	1	
Florence Mine - Ash	LF	Lead	0.001	1	0	
Florence Mine - Ash	LF	Mercury	0.002	1	0	
Florence Mine - Ash	LF	Molybdenum	0.01	1	1	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Florence Mine - Ash	LF	Nitrate/Nitrite	1.2	1	0	
Florence Mine - Ash	LF	Selenium	0.06	1	0	
Fran Site - FBC	LF	Aluminum	0.32	1	0	
Fran Site - FBC	LF	Antimony	0.005	1	1	
Fran Site - FBC	LF	Arsenic	0.02	1	0	
Fran Site - FBC	LF	Barium	0.08	1	0	
Fran Site - FBC	LF	Boron	0.43	1	0	
Fran Site - FBC	LF	Cadmium	0.005	1	1	
Fran Site - FBC	LF	Lead	0.005	1	1	
Fran Site - FBC	LF	Nitrate/Nitrite	1.22	1	0	
Fran Site - FBC	LF	Selenium	0.03	1	0	
FW - FBC	LF	Arsenic	0.02525	4	3	
FW - FBC	LF	Barium	0.304	4	0	
FW - FBC	LF	Cadmium	0.005	4	4	
FW - FBC	LF	Lead	0.05	4	4	
FW - FBC	LF	Mercury	0.001	4	4	
FW - FBC	LF	Selenium	0.1	4	4	
Gadsden - Ash	LF	Arsenic	0.2	1	0	
Gadsden - Ash	LF	Barium	0.3	1	0	
Gadsden - Ash	LF	Cadmium	0.01	1	0	
Gadsden - Ash	LF	Lead	0.04	1	0	
Gadsden - Ash	LF	Selenium	0.03	1	0	
Gale - Ash	LF	Aluminum	3.1	1	0	13630
Gale - Ash	LF	Antimony	0.03	1	0	3
Gale - Ash	LF	Arsenic	0.42	1	0	51.5
Gale - Ash	LF	Barium	1.7	1	0	143
Gale - Ash	LF	Boron	0.22	1	0	25
Gale - Ash	LF	Cadmium	0.01	1	0	1
Gale - Ash	LF	Lead	0.23	1	0	21
Gale - Ash	LF	Molybdenum	0.05	1	0	5
Gale - Ash	LF	Selenium	0.1	1	0	4.4
Gaston - Ash	LF	Arsenic	1.8	1	0	
Gaston - Ash	LF	Barium	0.3	1	0	
Gaston - Ash	LF	Cadmium	0.01	1	0	
Gaston - Ash	LF	Lead	0.05	1	0	
Gaston - Ash	LF	Selenium	0.003	1	0	
Gorgas - Ash	LF	Arsenic	1.6	1	0	
Gorgas - Ash	LF	Barium	0.3	1	0	
Gorgas - Ash	LF	Cadmium	0.01	1	0	
Gorgas - Ash	LF	Lead	0.04	1	0	
Gorgas - Ash	LF	Selenium	0.002	1	0	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Greene Co - Ash	LF	Arsenic	1.1	1	0	
Greene Co - Ash	LF	Barium	0.4	1	0	
Greene Co - Ash	LF	Cadmium	0.01	1	0	
Greene Co - Ash	LF	Lead	0.04	1	0	
Greene Co - Ash	LF	Selenium	0.003	1	0	
HA - Ash and Coal Refuse	LF	Aluminum	1.71925	4	0	5666.666667
HA - Ash and Coal Refuse	LF	Antimony	0.003905	4	2	
HA - Ash and Coal Refuse	LF	Arsenic	0.024975	4	0	9.666666667
HA - Ash and Coal Refuse	LF	Barium	1.01675	4	0	186.6666667
HA - Ash and Coal Refuse	LF	Boron	0.64545	4	0	14
HA - Ash and Coal Refuse	LF	Cadmium	0.0039275	4	0	0.25
HA - Ash and Coal Refuse	LF	Cobalt	0.01517875	4	1	
HA - Ash and Coal Refuse	LF	Lead	0.00378	4	2	8.7
HA - Ash and Coal Refuse	LF	Mercury	0.0001	4	0	0.065
HA - Ash and Coal Refuse	LF	Selenium	0.005025	4	0	0.534166667
HA - Ash and Coal Refuse	LF	Thallium	0.00196	8	8	
Hammond - Ash	LF	Arsenic	0.1	1	0	
Hammond - Ash	LF	Barium	0.3	1	0	
Hammond - Ash	LF	Cadmium	0.01	1	0	
Hammond - Ash	LF	Lead	0.05	1	0	
Hammond - Ash	LF	Selenium	0.02	1	0	
Harrim 3019 - Ash	LF	Aluminum	5.21	1	0	46577
Harrim 3019 - Ash	LF	Antimony	0.0058	1	0	646.4
Harrim 3019 - Ash	LF	Arsenic	0.178	1	0	50.43172727
Harrim 3019 - Ash	LF	Barium	0.32	1	0	319.89
Harrim 3019 - Ash	LF	Molybdenum	0.594	1	0	17.9
Harrim 3019 - Ash	LF	Nitrate/Nitrite	1.99	1	0	
Harrim 3019 - Ash	LF	Selenium	0.0468	1	0	1.405714286
Harrim 3019 - FBC	LF	Aluminum	0.67375	8	0	
Harrim 3019 - FBC	LF	Antimony	0.002	1	0	
Harrim 3019 - FBC	LF	Barium	0.465888889	9	0	
Harrim 3019 - FBC	LF	Boron	0.07	1	0	
Harrim 3019 - FBC	LF	Cobalt	0.1385	6	0	
Harrim 3019 - FBC	LF	Lead	0.24	5	0	
Harrim 3019 - FBC	LF	Molybdenum	0.347714286	7	0	
Harrim 3019 - FBC	LF	Nitrate/Nitrite	0.199333333	3	0	
Harrim 3019 - FBC	LF	Selenium	0.019	2	0	
Industry Mine - Ash	LF	Antimony	0.031597143	70	12	
Industry Mine - Ash	LF	Arsenic	0.050248454	97	51	
Industry Mine - Ash	LF	Barium	0.328329897	97	13	
Industry Mine - Ash	LF	Boron	4.719969072	97	0	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Industry Mine - Ash	LF	Cadmium	0.059061856	97	7	
Industry Mine - Ash	LF	Cobalt	0.120010309	97	30	
Industry Mine - Ash	LF	Lead	3.610544845	97	16	
Industry Mine - Ash	LF	Mercury	0.000284536	97	92	
Industry Mine - Ash	LF	Selenium	0.052408247	97	64	
Industry Mine - Ash	LF	Thallium	0.016984286	70	12	
Industry Mine - FBC	LF	Antimony	0.017077778	9	4	
Industry Mine - FBC	LF	Arsenic	0.031111111	9	7	
Industry Mine - FBC	LF	Barium	9.515666667	9	0	
Industry Mine - FBC	LF	Boron	2.813888889	9	2	
Industry Mine - FBC	LF	Cadmium	0.015888889	9	7	
Industry Mine - FBC	LF	Cobalt	0.029333333	9	8	
Industry Mine - FBC	LF	Lead	0.051877778	9	6	
Industry Mine - FBC	LF	Mercury	0.000222222	9	8	
Industry Mine - FBC	LF	Selenium	0.080388889	9	4	
Industry Mine - FBC	LF	Thallium	0.002288889	9	6	
Key West - Ash	LF	Arsenic	0.005	1	1	
Key West - Ash	LF	Barium	1	2	0	
Key West - Ash	LF	Boron	0.2	1	0	
Key West - Ash	LF	Cadmium	0.07	1	0	
Key West - Ash	LF	Lead	0.4	1	0	
Key West - Ash	LF	Mercury	0.18	1	0	
Key West - Ash	LF	Selenium	0.005	1	1	
Keystone - Ash	LF	Aluminum	2.059	4	0	
Keystone - Ash	LF	Antimony	0.036	1	0	
Keystone - Ash	LF	Arsenic	0.30925	4	0	
Keystone - Ash	LF	Barium	0.40375	4	0	
Keystone - Ash	LF	Boron	0.72	1	0	
Keystone - Ash	LF	Cadmium	0.009625	4	1	
Keystone - Ash	LF	Cobalt	0.023	1	0	
Keystone - Ash	LF	Lead	0.045375	4	1	
Keystone - Ash	LF	Mercury	0.001	1	1	
Keystone - Ash	LF	Molybdenum	0.32	1	0	
Keystone - Ash	LF	Selenium	0.0525	4	2	
Keystone - Ash	LF	Thallium	0.083	1	0	
Keystone - Ash and Coal Refuse	LF	Aluminum	0.842	4	0	
Keystone - Ash and Coal Refuse	LF	Antimony	0.0015	2	2	
Keystone - Ash and Coal Refuse	LF	Arsenic	0.01875	4	4	

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CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Keystone - Ash and Coal Refuse	LF	Barium	0.1925	4	0	
Keystone - Ash and Coal Refuse	LF	Boron	0.06	1	0	
Keystone - Ash and Coal Refuse	LF	Cadmium	0.00225	4	4	
Keystone - Ash and Coal Refuse	LF	Cobalt	0.022	1	0	
Keystone - Ash and Coal Refuse	LF	Lead	0.01875	4	4	
Keystone - Ash and Coal Refuse	LF	Mercury	0.001	1	1	
Keystone - Ash and Coal Refuse	LF	Molybdenum	0.01	2	2	
Keystone - Ash and Coal Refuse	LF	Selenium	0.02	4	4	
Keystone - Ash and Coal Refuse	LF	Thallium	0.028	1	0	
Kraft - Ash	LF	Arsenic	0.02	1	0	
Kraft - Ash	LF	Barium	0.3	1	0	
Kraft - Ash	LF	Cadmium	0.01	1	0	
Kraft - Ash	LF	Lead	0.04	1	0	
Kraft - Ash	LF	Selenium	0.04	1	0	
LIMB Site - Ash	LF	Aluminum	0.102894737	38	37	
LIMB Site - Ash	LF	Antimony	0.29	5	1	25
LIMB Site - Ash	LF	Arsenic	0.033594737	38	6	63
LIMB Site - Ash	LF	Barium	0.036552632	38	0	255
LIMB Site - Ash	LF	Boron	0.521842105	38	31	400
LIMB Site - Ash	LF	Cadmium	0.001031579	38	33	0.31
LIMB Site - Ash	LF	Cobalt	0.005131579	38	37	
LIMB Site - Ash	LF	Lead	0.012789474	38	25	14.5
LIMB Site - Ash	LF	Mercury	0.0001	2	2	
LIMB Site - Ash	LF	Molybdenum	1.527342105	38	1	2.5
LIMB Site - Ash	LF	Nitrate/Nitrite	26	2	0	
LIMB Site - Ash	LF	Selenium	0.0199	38	24	0.25
LIMB Site - Ash	LF	Thallium	0.05	5	5	
Little Sandy #10 Mine - Ash	LF	Aluminum	1.078	6	2	4541.666667
Little Sandy #10 Mine - Ash	LF	Arsenic	0.032336364	11	8	38.293
Little Sandy #10 Mine - Ash	LF	Barium	0.264454545	11	6	48.81
Little Sandy #10 Mine - Ash	LF	Boron	2.630909091	11	3	157.76
Little Sandy #10 Mine - Ash	LF	Cadmium	0.008290909	11	9	1.198
Little Sandy #10 Mine - Ash	LF	Lead	0.022009091	11	10	56.84
Little Sandy #10 Mine - Ash	LF	Mercury	0.000486364	11	10	0.24435

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CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Little Sandy #10 Mine - Ash	LF	Molybdenum	0.177272727	11	5	6.354
Little Sandy #10 Mine - Ash	LF	Selenium	0.059527273	11	9	6.531
Lone Mtn - Ash	LF	Aluminum	28.615	2	0	
Lone Mtn - Ash	LF	Antimony	0.033	2	0	
Lone Mtn - Ash	LF	Arsenic	0.185	2	0	76
Lone Mtn - Ash	LF	Barium	0.167	2	0	1483.2
Lone Mtn - Ash	LF	Cadmium	0.572	2	0	11.86
Lone Mtn - Ash	LF	Cobalt	0.142	2	0	87.3
Lone Mtn - Ash	LF	Mercury	0.0019	1	0	
Lone Mtn - Ash	LF	Molybdenum	0.4295	2	0	
Lone Mtn - Ash	LF	Selenium	0.328	2	0	
LS - Ash and Coal Refuse	LF	Aluminum	1.18	7	0	
LS - Ash and Coal Refuse	LF	Antimony	0.0107	4	0	
LS - Ash and Coal Refuse	LF	Arsenic	0.0104525	16	3	
LS - Ash and Coal Refuse	LF	Barium	0.13220625	16	0	
LS - Ash and Coal Refuse	LF	Boron	18.93125	16	0	
LS - Ash and Coal Refuse	LF	Cadmium	0.00148	16	15	
LS - Ash and Coal Refuse	LF	Cobalt	0.011125	4	0	
LS - Ash and Coal Refuse	LF	Lead	0.0025	16	16	
LS - Ash and Coal Refuse	LF	Mercury	0.00007	4	3	
LS - Ash and Coal Refuse	LF	Molybdenum	0.886875	16	0	
LS - Ash and Coal Refuse	LF	Nitrate/Nitrite	3.045	32	16	
LS - Ash and Coal Refuse	LF	Selenium	1.05343125	16	0	
LS - Ash and Coal Refuse	LF	Thallium	0.00185	8	8	
Martins Creek - Ash	LF	Aluminum	3.18335	20	2	114229.3889
Martins Creek - Ash	LF	Antimony	0.005021053	19	11	10.315
Martins Creek - Ash	LF	Arsenic	0.2314	20	1	50.50530556
Martins Creek - Ash	LF	Barium	0.1969	20	2	641.5466667
Martins Creek - Ash	LF	Boron	3.5089	20	1	304.1266667
Martins Creek - Ash	LF	Cadmium	0.0032	20	20	2.025
Martins Creek - Ash	LF	Cobalt	0.024722222	18	18	66.37611111
Martins Creek - Ash	LF	Lead	0.014	20	19	
Martins Creek - Ash	LF	Mercury	0.0001	19	19	
Martins Creek - Ash	LF	Molybdenum	0.195157895	19	10	
Martins Creek - Ash	LF	Nitrate/Nitrite	0.636428571	14	9	
Martins Creek - Ash	LF	Selenium	0.05717	20	8	4.043888889
Martins Creek - Ash	LF	Thallium	0.003263158	19	19	
McCloskey Site - FBC	LF	Aluminum	0.5	2	2	27450
McCloskey Site - FBC	LF	Arsenic	0.001	2	2	45.355
McCloskey Site - FBC	LF	Barium	0.1	2	2	32.55
McCloskey Site - FBC	LF	Boron	0.022	2	1	0.092

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
McCloskey Site - FBC	LF	Cadmium	0.0375	2	1	0.025
McCloskey Site - FBC	LF	Lead	0.05	2	2	50
McCloskey Site - FBC	LF	Mercury	0.25	2	2	0.4465
McCloskey Site - FBC	LF	Molybdenum	0.15	2	2	0.15
McCloskey Site - FBC	LF	Selenium	0.0515675	2	2	52.315
McDonough - Ash	LF	Arsenic	0.9	1	0	
McDonough - Ash	LF	Barium	0.5	1	0	
McDonough - Ash	LF	Cadmium	0.01	1	0	
McDonough - Ash	LF	Lead	0.04	1	0	
McDonough - Ash	LF	Selenium	0.2	1	0	
McIntosh - Ash	LF	Arsenic	0.09	1	0	
McIntosh - Ash	LF	Barium	0.2	1	0	
McIntosh - Ash	LF	Cadmium	0.6	1	0	
McIntosh - Ash	LF	Lead	0.03	1	0	
McIntosh - Ash	LF	Selenium	0.03	1	0	
McKay Site - FBC	LF	Aluminum	0.105	2	0	30000
McKay Site - FBC	LF	Antimony	0.01	2	2	2.5
McKay Site - FBC	LF	Arsenic	0.025	2	2	51.5
McKay Site - FBC	LF	Barium	0.27	2	0	215
McKay Site - FBC	LF	Boron	0.265	2	0	41.5
McKay Site - FBC	LF	Cadmium	0.005	2	2	2.5
McKay Site - FBC	LF	Lead	0.03	2	1	49
McKay Site - FBC	LF	Mercury	0.0001	2	2	0.345
McKay Site - FBC	LF	Molybdenum	0.13	2	0	6.25
McKay Site - FBC	LF	Nitrate/Nitrite	0.0175	2	1	
McKay Site - FBC	LF	Selenium	0.0355	2	1	1
Miller - Ash	LF	Arsenic	1.3	1	0	18
Miller - Ash	LF	Barium	0.1	1	0	7140
Miller - Ash	LF	Cadmium	0.09	1	0	1.6
Miller - Ash	LF	Lead	0.002	1	0	38
Miller - Ash	LF	Selenium	0.03	1	0	
Miller Creek Mine - Ash	LF	Aluminum	4.78597619	42	4	22486.5969
Miller Creek Mine - Ash	LF	Arsenic	0.075817021	47	16	60.54551064
Miller Creek Mine - Ash	LF	Barium	0.147255319	47	0	87.49382979
Miller Creek Mine - Ash	LF	Boron	2.343829787	47	3	167.0508511
Miller Creek Mine - Ash	LF	Cadmium	0.009771277	47	31	1.850959894
Miller Creek Mine - Ash	LF	Lead	0.034382979	47	24	51.50851064
Miller Creek Mine - Ash	LF	Mercury	0.000255319	47	46	0.06780663
Miller Creek Mine - Ash	LF	Molybdenum	0.166808511	47	17	9.819680851
Miller Creek Mine - Ash	LF	Selenium	0.047102128	47	23	6.492617021
Mine 26 - Ash	LF	Antimony	0.0125	6	6	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Mine 26 - Ash	LF	Arsenic	0.022333333	9	8	
Mine 26 - Ash	LF	Barium	0.388111111	9	1	
Mine 26 - Ash	LF	Boron	9.266666667	9	0	
Mine 26 - Ash	LF	Cadmium	0.008555556	9	4	
Mine 26 - Ash	LF	Cobalt	0.021744444	9	5	
Mine 26 - Ash	LF	Lead	0.148111111	9	6	
Mine 26 - Ash	LF	Mercury	0.0003	9	9	
Mine 26 - Ash	LF	Selenium	0.026388889	9	6	
Mine 26 - Ash	LF	Thallium	0.006833333	6	5	
Mine 26 - Ash and Coal Refuse	LF	Antimony	0.01	2	2	
Mine 26 - Ash and Coal Refuse	LF	Arsenic	0.054285714	7	5	
Mine 26 - Ash and Coal Refuse	LF	Barium	0.615714286	7	0	
Mine 26 - Ash and Coal Refuse	LF	Boron	3.504285714	7	0	
Mine 26 - Ash and Coal Refuse	LF	Cadmium	0.010142857	7	4	
Mine 26 - Ash and Coal Refuse	LF	Cobalt	0.032857143	7	2	
Mine 26 - Ash and Coal Refuse	LF	Lead	0.047142857	7	4	
Mine 26 - Ash and Coal Refuse	LF	Mercury	0.0001	7	7	
Mine 26 - Ash and Coal Refuse	LF	Selenium	0.02	7	7	
Mine 26 - Ash and Coal Refuse	LF	Thallium	0.005	2	2	
Mine 26 - FBC	LF	Arsenic	0.03	1	1	
Mine 26 - FBC	LF	Barium	0.51	1	0	
Mine 26 - FBC	LF	Boron	1.3	1	0	
Mine 26 - FBC	LF	Cadmium	0.0025	1	1	
Mine 26 - FBC	LF	Cobalt	0.005	1	1	
Mine 26 - FBC	LF	Lead	0.01	1	1	
Mine 26 - FBC	LF	Mercury	0.0001	1	1	
Mine 26 - FBC	LF	Selenium	0.08	1	0	
Mitchell - Ash	LF	Arsenic	1.3	1	0	
Mitchell - Ash	LF	Barium	0.3	1	0	
Mitchell - Ash	LF	Cadmium	0.01	1	0	
Mitchell - Ash	LF	Lead	0.06	1	0	
Mitchell - Ash	LF	Selenium	0.06	1	0	
MO - Ash and Coal Refuse	LF	Aluminum	4.49	2	0	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
MO - Ash and Coal Refuse	LF	Antimony	0.0125	2	0	
MO - Ash and Coal Refuse	LF	Arsenic	0.2855	2	0	
MO - Ash and Coal Refuse	LF	Barium	1.845	2	0	
MO - Ash and Coal Refuse	LF	Boron	0.219	2	0	
MO - Ash and Coal Refuse	LF	Cadmium	0.006	2	0	
MO - Ash and Coal Refuse	LF	Cobalt	0.012	2	0	
MO - Ash and Coal Refuse	LF	Lead	0.0065	2	0	
MO - Ash and Coal Refuse	LF	Mercury	0.00005	4	4	
MO - Ash and Coal Refuse	LF	Selenium	0.1312	2	0	
MO - Ash and Coal Refuse	LF	Thallium	0.01415	2	0	
Murdock Mine - Ash	LF	Antimony	0.0076875	8	8	
Murdock Mine - Ash	LF	Arsenic	0.0080875	8	6	
Murdock Mine - Ash	LF	Barium	0.258625	8	0	
Murdock Mine - Ash	LF	Boron	9.38775	8	0	
Murdock Mine - Ash	LF	Cadmium	0.0458	8	2	
Murdock Mine - Ash	LF	Cobalt	0.0225625	8	2	
Murdock Mine - Ash	LF	Lead	0.00555	8	2	
Murdock Mine - Ash	LF	Mercury	0.0004375	8	8	
Murdock Mine - Ash	LF	Selenium	0.0053875	8	4	
Murdock Mine - Ash	LF	Thallium	0.02325	8	2	
Murdock Mine - FBC	LF	Antimony	0.004	3	3	
Murdock Mine - FBC	LF	Arsenic	0.005	3	3	
Murdock Mine - FBC	LF	Barium	0.368333333	3	0	
Murdock Mine - FBC	LF	Boron	0.436666667	3	0	
Murdock Mine - FBC	LF	Cadmium	0.0015	3	3	
Murdock Mine - FBC	LF	Cobalt	0.0025	3	3	
Murdock Mine - FBC	LF	Lead	0.0015	3	3	
Murdock Mine - FBC	LF	Mercury	0.0004	3	3	
Murdock Mine - FBC	LF	Selenium	0.003533333	3	2	
Murdock Mine - FBC	LF	Thallium	0.005	3	3	
Nepco - FBC	LF	Arsenic	0.025	2	2	21
Nepco - FBC	LF	Cadmium	0.01	1	0	0.5
Nepco - FBC	LF	Lead	0.025	2	2	39
Nepco - FBC	LF	Mercury	0.0002	2	2	0.01
Nepco - FBC	LF	Selenium	0.05	2	2	12.6
No. 1 Contracting Corp - FBC	LF	Aluminum	0.935	2	0	
No. 1 Contracting Corp - FBC	LF	Antimony	0.018	1	0	
No. 1 Contracting Corp - FBC	LF	Arsenic	0.046	2	0	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
No. 1 Contracting Corp - FBC	LF	Barium	0.1315	2	0	
No. 1 Contracting Corp - FBC	LF	Boron	0.05	1	0	
No. 1 Contracting Corp - FBC	LF	Cadmium	0.005	1	0	
No. 1 Contracting Corp - FBC	LF	Lead	0.06	1	0	
No. 1 Contracting Corp - FBC	LF	Mercury	0.0002	1	0	
No. 1 Contracting Corp - FBC	LF	Molybdenum	0.105	2	0	
No. 1 Contracting Corp - FBC	LF	Selenium	0.1395	2	0	
Northampton40000201 - Ash	LF	Aluminum	0.38	1	0	24500
Northampton40000201 - Ash	LF	Antimony	0.01	1	0	20
Northampton40000201 - Ash	LF	Arsenic	0.005	1	0	40.6
Northampton40000201 - Ash	LF	Barium	0.21	1	0	242
Northampton40000201 - Ash	LF	Boron	0.2	1	0	17.3
Northampton40000201 - Ash	LF	Cadmium	0.012	1	0	0.5
Northampton40000201 - Ash	LF	Lead	0.1	1	0	18
Northampton40000201 - Ash	LF	Mercury	0.0002	1	0	0.535
Northampton40000201 - Ash	LF	Molybdenum	0.1	1	0	10
Northampton40000201 - Ash	LF	Selenium	0.015	1	0	8.9
Nucla - FBC	LF	Aluminum	0.1	2	2	110050
Nucla - FBC	LF	Arsenic	0.0025	4	4	7.4
Nucla - FBC	LF	Barium	0.08	2	1	190
Nucla - FBC	LF	Boron	0.485	2	1	57.5
Nucla - FBC	LF	Cadmium	0.00055	2	2	1.95
Nucla - FBC	LF	Cobalt	0.005	2	2	10
Nucla - FBC	LF	Lead	0.0016	2	1	35.5
Nucla - FBC	LF	Mercury	0.0001	2	2	
Nucla - FBC	LF	Molybdenum	0.2045	2	0	83
Nucla - FBC	LF	Nitrate/Nitrite	0.1125	2	2	
Nucla - FBC	LF	Selenium	0.00485	2	1	9.35

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Nucla2 - FBC	LF	Aluminum	7.18	3	0	100000
Nucla2 - FBC	LF	Antimony	0.1	6	6	46
Nucla2 - FBC	LF	Arsenic	0.00375	6	5	27.93333333
Nucla2 - FBC	LF	Barium	0.093	3	0	246
Nucla2 - FBC	LF	Boron	3.1	3	1	69.16666667
Nucla2 - FBC	LF	Cadmium	0.000475	6	4	0.263333333
Nucla2 - FBC	LF	Cobalt	0.012	3	1	6.1
Nucla2 - FBC	LF	Lead	0.0062	3	0	8.296666667
Nucla2 - FBC	LF	Mercury	0.000566667	6	5	0.214166667
Nucla2 - FBC	LF	Molybdenum	0.303333333	3	0	3.316666667
Nucla2 - FBC	LF	Nitrate/Nitrite	6.591666667	6	4	
Nucla2 - FBC	LF	Selenium	0.048666667	6	2	1.395
Nucla2 - FBC	LF	Thallium	0.05	3	3	6.416666667
OK - Ash	LF	Aluminum	11.895	2	0	
OK - Ash	LF	Antimony	0.001575	2	1	
OK - Ash	LF	Arsenic	0.003225	2	1	
OK - Ash	LF	Barium	0.686	2	0	
OK - Ash	LF	Boron	2.68	2	0	
OK - Ash	LF	Cadmium	0.00027	2	1	
OK - Ash	LF	Cobalt	0.00745	2	0	
OK - Ash	LF	Lead	0.00355	2	0	
OK - Ash	LF	Mercury	0.0001	2	1	
OK - Ash	LF	Selenium	0.037	2	0	
OK - Ash	LF	Thallium	0.00185	4	4	
P4 - Ash	LF	Aluminum	6.2196875	8	0	
P4 - Ash	LF	Antimony	0.00105	4	4	
P4 - Ash	LF	Arsenic	0.00420375	8	5	
P4 - Ash	LF	Barium	0.254375	8	0	
P4 - Ash	LF	Boron	1.142697917	8	0	
P4 - Ash	LF	Cadmium	0.00125	8	8	
P4 - Ash	LF	Cobalt	0.00315	2	0	
P4 - Ash	LF	Lead	0.0025	8	8	
P4 - Ash	LF	Mercury	0.00005	4	4	
P4 - Ash	LF	Molybdenum	0.2114375	8	4	
P4 - Ash	LF	Nitrate/Nitrite	1.92075	16	8	
P4 - Ash	LF	Selenium	0.01	8	8	
P4 - Ash	LF	Thallium	0.002775	2	2	
PA - Ash	LF	Aluminum	26.16153846	13	0	
PA - Ash	LF	Antimony	0.0031	2	0	
PA - Ash	LF	Arsenic	0.005991923	13	9	
PA - Ash	LF	Barium	1.043838462	13	0	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
PA - Ash	LF	Boron	0.736153846	13	0	
PA - Ash	LF	Cadmium	0.001758462	13	12	
PA - Ash	LF	Cobalt	0.001915	2	2	
PA - Ash	LF	Lead	0.005993077	13	10	
PA - Ash	LF	Mercury	0.000175	2	0	
PA - Ash	LF	Molybdenum	0.138461538	13	4	
PA - Ash	LF	Nitrate/Nitrite	2.544596154	26	15	
PA - Ash	LF	Selenium	0.084376923	13	5	
PA - Ash	LF	Thallium	0.00196	4	4	
Pitt - FBC	LF	Antimony	0.0219	1	0	
Pitt - FBC	LF	Arsenic	0.05	1	1	
Pitt - FBC	LF	Barium	1.167333333	3	1	
Pitt - FBC	LF	Cadmium	0.033333333	3	3	
Pitt - FBC	LF	Lead	0.183333333	3	3	
Pitt - FBC	LF	Mercury	0.005	1	1	
Pitt - FBC	LF	Selenium	0.05	1	1	
Pitt - FBC	LF	Thallium	0.0025	3	3	
Plant 10 - FBC	LF	Arsenic	0.14875	4	0	71.3
Plant 10 - FBC	LF	Cadmium	0.05425	4	1	2.418181818
Plant 10 - FBC	LF	Lead	0.2965	4	1	39.63636364
Plant 10 - FBC	LF	Mercury	0.05005	4	4	1.174
Plant 10 - FBC	LF	Selenium	0.1285	4	0	4.011818182
Plant 12 - FBC	LF	Arsenic	0.004125	8	4	98.62222222
Plant 12 - FBC	LF	Cadmium	0.02	8	8	2.188888889
Plant 12 - FBC	LF	Lead	0.28375	8	2	47.83333333
Plant 12 - FBC	LF	Mercury	0.0004	8	8	1.047777778
Plant 12 - FBC	LF	Selenium	0.006125	8	8	4.263888889
Plant 8 - FBC	LF	Arsenic	0.019868421	19	18	42.04210526
Plant 8 - FBC	LF	Cadmium	0.016826923	52	43	2.288947368
Plant 8 - FBC	LF	Lead	0.007211538	52	37	27.62105263
Plant 8 - FBC	LF	Mercury	0.000289474	19	19	0.065789474
Plant 8 - FBC	LF	Selenium	0.053026316	19	9	33.02263158
Plant 9 - FBC	LF	Arsenic	0.058666667	3	0	2.8
Plant 9 - FBC	LF	Lead	0.105454545	11	8	57.67142857
Plant 9 - FBC	LF	Mercury	0.00025	11	11	0.604285714
Plant 9 - FBC	LF	Selenium	0.065333333	3	0	5.115714286
Portland - Ash	LF	Aluminum	2.648555556	9	0	
Portland - Ash	LF	Antimony	0.075	2	2	
Portland - Ash	LF	Arsenic	0.178666667	9	6	
Portland - Ash	LF	Barium	0.28475	8	0	
Portland - Ash	LF	Boron	4.799333333	3	0	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Portland - Ash	LF	Cadmium	0.006	9	7	
Portland - Ash	LF	Cobalt	0.014	2	1	
Portland - Ash	LF	Lead	0.058333333	9	8	
Portland - Ash	LF	Mercury	0.001	4	4	
Portland - Ash	LF	Molybdenum	0.178666667	3	1	
Portland - Ash	LF	Selenium	0.25625	4	4	
Portland - Ash	LF	Thallium	0.005	4	4	
PP - Ash	LF	Aluminum	2.422	2	0	
PP - Ash	LF	Antimony	0.00245	2	0	
PP - Ash	LF	Arsenic	0.0273375	2	1	
PP - Ash	LF	Barium	0.2435	2	0	
PP - Ash	LF	Boron	6.605	2	0	
PP - Ash	LF	Cadmium	0.0023975	2	1	
PP - Ash	LF	Cobalt	0.0049575	2	1	
PP - Ash	LF	Lead	0.001155	2	1	
PP - Ash	LF	Mercury	0.00028	2	0	
PP - Ash	LF	Selenium	0.0364	2	0	
PP - Ash	LF	Thallium	0.01518	2	1	
Revloc Site - FBC	LF	Aluminum	0.58	2	1	
Revloc Site - FBC	LF	Antimony	0.002	2	2	
Revloc Site - FBC	LF	Arsenic	0.002	2	1	
Revloc Site - FBC	LF	Barium	0.44	2	2	
Revloc Site - FBC	LF	Boron	0.2585	2	1	
Revloc Site - FBC	LF	Cadmium	0.02	2	2	
Revloc Site - FBC	LF	Cobalt	0.0825	2	1	
Revloc Site - FBC	LF	Lead	0.25	2	0	
Revloc Site - FBC	LF	Mercury	0.0005	2	2	
Revloc Site - FBC	LF	Molybdenum	0.0545	2	1	
Revloc Site - FBC	LF	Selenium	0.0025	2	1	
Scherer - Ash	LF	Arsenic	0.01	1	0	
Scherer - Ash	LF	Barium	0.7	1	0	
Scherer - Ash	LF	Cadmium	0.001	1	0	
Scherer - Ash	LF	Lead	0.001	1	0	
Scherer - Ash	LF	Selenium	0.06	1	0	
Scholz - Ash	LF	Arsenic	0.02	1	0	
Scholz - Ash	LF	Barium	0.2	1	0	
Scholz - Ash	LF	Cadmium	0.04	1	0	
Scholz - Ash	LF	Lead	0.04	1	0	
Scholz - Ash	LF	Selenium	0.02	1	0	
Scrubgrass - FBC	LF	Arsenic	0.025	2	2	59
Scrubgrass - FBC	LF	Cadmium	0.0025	1	0	0.7

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Scrubgrass - FBC	LF	Lead	0.025	2	2	50
Scrubgrass - FBC	LF	Mercury	0.0002	2	2	0.01
Scrubgrass - FBC	LF	Selenium	0.05	2	2	21.7
Seward - Ash	LF	Aluminum	2.965	2	0	
Seward - Ash	LF	Antimony	0.075	2	2	
Seward - Ash	LF	Arsenic	0.288666667	3	2	
Seward - Ash	LF	Barium	0.473333333	3	0	
Seward - Ash	LF	Boron	0.57	1	0	
Seward - Ash	LF	Cadmium	0.005833333	3	1	
Seward - Ash	LF	Cobalt	0.014	1	0	
Seward - Ash	LF	Lead	0.1875	1	1	
Seward - Ash	LF	Mercury	0.003733333	3	3	
Seward - Ash	LF	Molybdenum	0.53	1	0	
Seward - Ash	LF	Selenium	0.196666667	3	2	
Seward - Ash	LF	Thallium	0.012	1	0	
Shawnee - FBC	LF	Aluminum	0.231	5	3	38240
Shawnee - FBC	LF	Antimony	0.296	5	2	15.6
Shawnee - FBC	LF	Arsenic	0.219	10	6	17.3
Shawnee - FBC	LF	Barium	2.001	10	0	799.4
Shawnee - FBC	LF	Boron	0.97	5	3	116.2
Shawnee - FBC	LF	Cadmium	0.005555	10	7	0.622
Shawnee - FBC	LF	Cobalt	0.07	5	2	2.75
Shawnee - FBC	LF	Lead	0.0897	10	5	6.4
Shawnee - FBC	LF	Mercury	0.00029	10	8	0.365
Shawnee - FBC	LF	Molybdenum	0.382	5	0	6.4
Shawnee - FBC	LF	Nitrate/Nitrite	3.786666667	8	4	
Shawnee - FBC	LF	Selenium	0.13005	10	6	0.73
Shawnee - FBC	LF	Thallium	0.197	5	3	8.9
Shawville - Ash	LF	Aluminum	2.0958	5	0	
Shawville - Ash	LF	Antimony	0.075	2	2	
Shawville - Ash	LF	Arsenic	0.4384	5	1	
Shawville - Ash	LF	Barium	0.2172	5	0	
Shawville - Ash	LF	Boron	0.56	1	0	
Shawville - Ash	LF	Cadmium	0.0059	5	2	
Shawville - Ash	LF	Cobalt	0.021	1	0	
Shawville - Ash	LF	Lead	0.1875	1	1	
Shawville - Ash	LF	Mercury	0.001	2	2	
Shawville - Ash	LF	Molybdenum	0.09	1	0	
Shawville - Ash	LF	Selenium	0.191	5	2	
Shawville - Ash	LF	Thallium	0.005	2	2	
Sibley Quarry - Ash	LF	Aluminum	0.6	4	4	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Sibley Quarry - Ash	LF	Arsenic	0.018	4	0	
Sibley Quarry - Ash	LF	Barium	0.265	4	4	
Sibley Quarry - Ash	LF	Cadmium	0.00114125	4	2	
Sibley Quarry - Ash	LF	Lead	0.00305	4	4	
Sibley Quarry - Ash	LF	Mercury	0.0001	4	4	
Sibley Quarry - Ash	LF	Molybdenum	0.725	3	1	
Sibley Quarry - Ash	LF	Selenium	0.18425	4	1	
Silverton - Ash	LF	Aluminum	3.1	1	0	16870
Silverton - Ash	LF	Arsenic	0.375	2	0	48.5
Silverton - Ash	LF	Barium	1.7	1	0	181.5
Silverton - Ash	LF	Boron	0.22	1	0	20.5
Silverton - Ash	LF	Lead	0.23	1	0	29.5
Silverton - Ash	LF	Molybdenum	0.1	1	0	5
Silverton - Ash	LF	Selenium	0.12	2	0	6.7
Smith - Ash	LF	Arsenic	0.02	1	0	
Smith - Ash	LF	Barium	0.2	1	0	
Smith - Ash	LF	Cadmium	0.04	1	0	
Smith - Ash	LF	Lead	0.01	1	0	
Smith - Ash	LF	Selenium	0.01	1	0	
SW - Ash	LF	Arsenic	0.006679487	195	53	29.495189
SW - Ash	LF	Barium	0.81082716	243	0	2538.862069
SW - Ash	LF	Cadmium	0.003400769	195	47	1.230670103
SW - Ash	LF	Lead	0.001570707	99	97	35.39886598
SW - Ash	LF	Mercury	0.000217677	99	98	0.039255034
SW - Ash	LF	Selenium	0.003534884	172	46	0.6
SX - Ash	LF	Aluminum	1.862	2	0	
SX - Ash	LF	Antimony	0.003275	2	1	
SX - Ash	LF	Arsenic	0.0365	2	0	
SX - Ash	LF	Barium	0.959	2	0	
SX - Ash	LF	Boron	4.5223	2	0	
SX - Ash	LF	Cadmium	0.04425	2	0	
SX - Ash	LF	Cobalt	0.0167	2	0	
SX - Ash	LF	Lead	0.00675	2	0	
SX - Ash	LF	Mercury	0.00005	4	4	
SX - Ash	LF	Selenium	0.048725	2	1	
SX - Ash	LF	Thallium	0.013625	2	1	
Tidd - FBC	LF	Aluminum	0.105	3	1	
Tidd - FBC	LF	Antimony	0.03	5	5	
Tidd - FBC	LF	Arsenic	0.028333333	3	2	
Tidd - FBC	LF	Barium	0.184	2	0	
Tidd - FBC	LF	Boron	0.82	3	0	

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CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Tidd - FBC	LF	Cadmium	0.0015	3	3	
Tidd - FBC	LF	Cobalt	0.021	3	0	
Tidd - FBC	LF	Lead	0.015833333	3	3	
Tidd - FBC	LF	Mercury	0.006733333	3	3	
Tidd - FBC	LF	Molybdenum	0.082	3	0	
Tidd - FBC	LF	Selenium	0.101666667	3	2	
Titus - Ash	LF	Aluminum	4.4135	4	0	
Titus - Ash	LF	Antimony	0.04375	4	4	
Titus - Ash	LF	Arsenic	0.346	2	1	
Titus - Ash	LF	Barium	0.3	4	0	
Titus - Ash	LF	Boron	7.345	2	0	
Titus - Ash	LF	Cadmium	0.0115	4	0	
Titus - Ash	LF	Cobalt	0.027	2	0	
Titus - Ash	LF	Lead	0.19375	2	2	
Titus - Ash	LF	Mercury	0.001	2	2	
Titus - Ash	LF	Molybdenum	0.34	2	0	
Titus - Ash	LF	Selenium	0.144	4	3	
Titus - Ash	LF	Thallium	0.01	2	0	
Tracy Vein Slope - Ash	LF	Aluminum	0.533833333	6	0	11090
Tracy Vein Slope - Ash	LF	Antimony	0.05	5	0	24.215
Tracy Vein Slope - Ash	LF	Arsenic	0.065166667	6	0	61.33333333
Tracy Vein Slope - Ash	LF	Barium	0.148833333	6	0	99.31666667
Tracy Vein Slope - Ash	LF	Boron	1.4486	5	0	122.4333333
Tracy Vein Slope - Ash	LF	Cadmium	0.044833333	6	0	1.070166667
Tracy Vein Slope - Ash	LF	Lead	0.075	6	0	18.90833333
Tracy Vein Slope - Ash	LF	Mercury	0.001	2	0	1.5888
Tracy Vein Slope - Ash	LF	Molybdenum	0.1662	5	0	7.721666667
Tracy Vein Slope - Ash	LF	Selenium	0.0524	5	0	8.608
Tracy Vein Slope - FBC	LF	Aluminum	1.32	1	0	7240
Tracy Vein Slope - FBC	LF	Arsenic	0.052	1	0	6.97
Tracy Vein Slope - FBC	LF	Barium	0.056	1	0	68.9
Tracy Vein Slope - FBC	LF	Boron	0.043	1	0	7.43
Tracy Vein Slope - FBC	LF	Molybdenum	0.027	1	0	0.84
Tracy Vein Slope - FBC	LF	Selenium	0.039	1	0	3.22
UAPP - Ash	LF	Arsenic	0.0025	2	2	
UAPP - Ash	LF	Barium	0.4	2	1	
UAPP - Ash	LF	Cadmium	0.04	2	2	
UAPP - Ash	LF	Lead	0.1	2	2	
UAPP - Ash	LF	Mercury	0.025	2	2	
UAPP - Ash	LF	Selenium	0.00275	2	1	
Universal - Ash	LF	Aluminum	2.057777778	9	0	6000.222222

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CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Universal - Ash	LF	Arsenic	0.277818182	11	2	41.50909091
Universal - Ash	LF	Barium	0.090181818	11	1	71
Universal - Ash	LF	Boron	2.754545455	11	0	180.2954545
Universal - Ash	LF	Cadmium	0.003227273	11	9	2.115909091
Universal - Ash	LF	Lead	0.022145455	11	7	33.00909091
Universal - Ash	LF	Mercury	0.000386364	11	11	0.137272727
Universal - Ash	LF	Molybdenum	0.134363636	11	1	3.554545455
Universal - Ash	LF	Selenium	0.160090909	11	2	7.106363636
Wansley - Ash	LF	Arsenic	0.05	1	0	
Wansley - Ash	LF	Barium	0.2	1	0	
Wansley - Ash	LF	Cadmium	0.09	1	0	
Wansley - Ash	LF	Lead	0.02	1	0	
Wansley - Ash	LF	Selenium	0.06	1	0	
WEPCO CALEDONIA LANDFILL - Ash	LF	Barium	0.225	2	0	
WEPCO CALEDONIA LANDFILL - Ash	LF	Boron	16.90454545	22	0	
WEPCO CALEDONIA LANDFILL - Ash	LF	Cadmium	0.000045	3	3	
WEPCO CALEDONIA LANDFILL - Ash	LF	Lead	0.003566667	3	3	
WEPCO CALEDONIA LANDFILL - Ash	LF	Molybdenum	0.77500575	4	3	
WEPCO CALEDONIA LANDFILL - Ash	LF	Selenium	0.046794118	34	0	
WEPCO HWY 32 LANDFILL - Ash	LF	Boron	83.41666667	12	0	
WEPCO HWY 32 LANDFILL - Ash	LF	Selenium	0.006675	12	4	
WEPCO SYSTEMS CONTROL CENTER A - Ash	LF	Arsenic	0.0055	2	0	
WEPCO SYSTEMS CONTROL CENTER A - Ash	LF	Barium	0.1195	2	0	
WEPCO SYSTEMS CONTROL CENTER A - Ash	LF	Boron	14.02134483	29	0	
WEPCO SYSTEMS CONTROL CENTER A - Ash	LF	Cadmium	0.010266667	3	1	
WEPCO SYSTEMS CONTROL CENTER A - Ash	LF	Lead	0.00625	2	1	

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CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
WEPCO SYSTEMS CONTROL CENTER A - Ash	LF	Mercury	0.0002	1	0	
WEPCO SYSTEMS CONTROL CENTER A - Ash	LF	Molybdenum	0.000022375	4	4	
WEPCO SYSTEMS CONTROL CENTER A - Ash	LF	Nitrate/Nitrite	1.866666667	3	0	
WEPCO SYSTEMS CONTROL CENTER A - Ash	LF	Selenium	0.06332275	28	0	
Wilton Site - Ash	LF	Aluminum	3	1	0	
Wilton Site - Ash	LF	Arsenic	0.027	1	0	
Wilton Site - Ash	LF	Barium	0.51	1	0	
Wilton Site - Ash	LF	Boron	25	1	0	
Wilton Site - Ash	LF	Cadmium	0.0025	2	2	
Wilton Site - Ash	LF	Lead	0.0025	2	2	
Wilton Site - Ash	LF	Mercury	0.001	2	2	
Wilton Site - Ash	LF	Molybdenum	0.34	1	0	
Wilton Site - Ash	LF	Nitrate/Nitrite	0.5	1	1	
Wilton Site - Ash	LF	Selenium	0.09	1	0	
WIS PUBLIC SERV CORP-WESTON AS - Ash	LF	Arsenic	0.0014	3	2	
WIS PUBLIC SERV CORP-WESTON AS - Ash	LF	Barium	0.183025	4	1	
WIS PUBLIC SERV CORP-WESTON AS - Ash	LF	Boron	6.363333333	21	1	
WIS PUBLIC SERV CORP-WESTON AS - Ash	LF	Cadmium	0.0047595	8	0	
WIS PUBLIC SERV CORP-WESTON AS - Ash	LF	Lead	0.00668375	8	0	
WIS PUBLIC SERV CORP-WESTON AS - Ash	LF	Mercury	0.000082	5	5	
WIS PUBLIC SERV CORP-WESTON AS - Ash	LF	Selenium	0.011077619	21	1	
Yates1 - Ash	LF	Arsenic	0.1	1	0	
Yates1 - Ash	LF	Barium	0.3	1	0	
Yates1 - Ash	LF	Cadmium	0.02	1	0	
Yates1 - Ash	LF	Lead	0.05	1	0	
Yates1 - Ash	LF	Selenium	0.02	1	0	
Yates2 - Ash	LF	Arsenic	0.09	1	0	
Yates2 - Ash	LF	Barium	0.2	1	0	
Yates2 - Ash	LF	Cadmium	0.02	1	0	
Yates2 - Ash	LF	Lead	0.03	1	0	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Yates2 - Ash	LF	Selenium	0.05	1	0	
AP - Ash	SI	Aluminum	0.553384615	13	0	
AP - Ash	SI	Antimony	0.01	1	1	
AP - Ash	SI	Arsenic	0.070933333	15	0	
AP - Ash	SI	Barium	0.063066667	15	1	
AP - Ash	SI	Boron	12.50986667	15	0	
AP - Ash	SI	Cadmium	0.001042857	14	7	
AP - Ash	SI	Cobalt	0.01	1	1	
AP - Ash	SI	Lead	0.001723333	15	14	
AP - Ash	SI	Molybdenum	0.486733333	15	2	
AP - Ash	SI	Nitrate/Nitrite	0.254809524	29	22	
AP - Ash	SI	Selenium	0.044326667	15	1	
AP - Ash	SI	Thallium	0.0025	1	1	
BR - Ash and Coal Refuse	SI	Aluminum	89.12777778	18	0	
BR - Ash and Coal Refuse	SI	Arsenic	0.775383333	15	4	
BR - Ash and Coal Refuse	SI	Barium	0.188055556	18	14	
BR - Ash and Coal Refuse	SI	Boron	3.857694444	18	2	
BR - Ash and Coal Refuse	SI	Cadmium	0.175	18	7	
BR - Ash and Coal Refuse	SI	Cobalt	0.204722222	18	11	
BR - Ash and Coal Refuse	SI	Molybdenum	0.5	18	18	
C - Ash	SI	Aluminum	4.192307692	13	0	
C - Ash	SI	Antimony	0.07	10	10	
C - Ash	SI	Arsenic	0.15	10	0	
C - Ash	SI	Barium	0.113769231	13	0	
C - Ash	SI	Boron	10.96428571	14	0	
C - Ash	SI	Cadmium	0.0025	10	10	
C - Ash	SI	Cobalt	0.005	10	10	
C - Ash	SI	Lead	0.00229	10	5	
C - Ash	SI	Molybdenum	0.585384615	13	0	
C - Ash	SI	Nitrate/Nitrite	10.85474359	16	3	
C - Ash	SI	Selenium	0.0175	10	2	
C - Ash	SI	Thallium	0.05	10	10	
CADK - Ash	SI	Aluminum	0.165	2	0	
CADK - Ash	SI	Arsenic	0.0075	2	2	
CADK - Ash	SI	Barium	0.02	2	2	
CADK - Ash	SI	Boron	60.05	2	0	
CADK - Ash	SI	Cadmium	0.001	2	2	
CADK - Ash	SI	Lead	0.1	2	2	
CADK - Ash	SI	Molybdenum	1.165	2	0	
CADK - Ash	SI	Nitrate/Nitrite	11.135	4	0	
CADK - Ash	SI	Selenium	0.125	2	0	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
CASJ - Ash	SI	Aluminum	0.1108	5	4	
CASJ - Ash	SI	Arsenic	5.37225	4	0	
CASJ - Ash	SI	Barium	0.0214	5	2	
CASJ - Ash	SI	Boron	46.02	5	0	
CASJ - Ash	SI	Cadmium	0.0156	5	3	
CASJ - Ash	SI	Lead	0.21	5	4	
CASJ - Ash	SI	Molybdenum	0.13	5	5	
CASJ - Ash	SI	Nitrate/Nitrite	1.882	10	8	
CASJ - Ash	SI	Selenium	0.40575	4	0	
CATT - Ash	SI	Aluminum	0.28	2	0	
CATT - Ash	SI	Arsenic	0.206	2	0	
CATT - Ash	SI	Barium	0.085	2	0	
CATT - Ash	SI	Boron	110.5	2	0	
CATT - Ash	SI	Cadmium	0.002	2	1	
CATT - Ash	SI	Lead	0.2275	2	0	
CATT - Ash	SI	Molybdenum	0.655	2	0	
CATT - Ash	SI	Nitrate/Nitrite	0.01	2	0	
CATT - Ash	SI	Selenium	1.025	2	0	
CL - Ash and Coal Refuse	SI	Aluminum	4.680970556	30	2	
CL - Ash and Coal Refuse	SI	Arsenic	0.493663408	30	2	
CL - Ash and Coal Refuse	SI	Barium	0.550251717	30	0	
CL - Ash and Coal Refuse	SI	Boron	1.092075	30	0	
CL - Ash and Coal Refuse	SI	Cadmium	0.001680507	30	27	
CL - Ash and Coal Refuse	SI	Lead	0.003384333	30	29	
CL - Ash and Coal Refuse	SI	Molybdenum	0.377590556	30	0	
CL - Ash and Coal Refuse	SI	Nitrate/Nitrite	0.6303	60	13	
CL - Ash and Coal Refuse	SI	Selenium	0.147525085	30	9	
CY - Ash	SI	Aluminum	6.0975	4	0	
CY - Ash	SI	Arsenic	0.1975	4	0	
CY - Ash	SI	Barium	0.179725	4	0	
CY - Ash	SI	Boron	0.025	4	4	
CY - Ash	SI	Cadmium	0.0040625	4	4	
CY - Ash	SI	Lead	0.008125	4	4	
CY - Ash	SI	Molybdenum	0.655	4	0	
CY - Ash	SI	Nitrate/Nitrite	750.2625	8	5	
CY - Ash	SI	Selenium	0.086575	4	1	
FC - Ash and Coal Refuse	SI	Aluminum	11.433	10	0	
FC - Ash and Coal Refuse	SI	Arsenic	0.00752	10	8	
FC - Ash and Coal Refuse	SI	Barium	0.14918	10	0	
FC - Ash and Coal Refuse	SI	Boron	0.7445	10	1	
FC - Ash and Coal Refuse	SI	Cadmium	0.001956	10	9	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
FC - Ash and Coal Refuse	SI	Lead	0.0025	10	10	
FC - Ash and Coal Refuse	SI	Molybdenum	0.2275	10	10	
FC - Ash and Coal Refuse	SI	Nitrate/Nitrite	0.2	20	20	
FC - Ash and Coal Refuse	SI	Selenium	0.02174	10	0	
HA - Ash	SI	Aluminum	2.830833333	9	2	
HA - Ash	SI	Arsenic	0.086774333	9	2	
HA - Ash	SI	Barium	0.471945556	9	0	
HA - Ash	SI	Boron	2.283583333	9	0	
HA - Ash	SI	Cadmium	0.00125	9	9	
HA - Ash	SI	Lead	0.003503333	9	8	
HA - Ash	SI	Molybdenum	0.107333333	9	4	
HA - Ash	SI	Nitrate/Nitrite	1.968222222	18	10	
HA - Ash	SI	Selenium	0.01	9	9	
HA - Ash and Coal Refuse	SI	Aluminum	0.65	1	0	
HA - Ash and Coal Refuse	SI	Arsenic	0.18	1	0	
HA - Ash and Coal Refuse	SI	Barium	0.11	1	0	
HA - Ash and Coal Refuse	SI	Boron	1.7	1	0	
HA - Ash and Coal Refuse	SI	Cadmium	0.0025	1	1	
HA - Ash and Coal Refuse	SI	Lead	0.025	1	1	
HA - Ash and Coal Refuse	SI	Mercury	0.00025	1	1	
HA - Ash and Coal Refuse	SI	Molybdenum	0.075	1	1	
HA - Ash and Coal Refuse	SI	Selenium	0.0025	1	1	
L - Ash	SI	Aluminum	0.015	2	2	
L - Ash	SI	Barium	0.001	2	2	
L - Ash	SI	Boron	0.62	2	0	
L - Ash	SI	Cadmium	0.001	2	2	
L - Ash	SI	Molybdenum	0.1675	2	1	
MO - Ash	SI	Aluminum	0.894458333	6	0	
MO - Ash	SI	Arsenic	0.011755993	6	3	
MO - Ash	SI	Barium	0.019379487	6	0	
MO - Ash	SI	Boron	0.085041667	6	2	
MO - Ash	SI	Cadmium	0.00125	6	6	
MO - Ash	SI	Lead	0.003666667	6	5	
MO - Ash	SI	Molybdenum	0.928770833	6	3	
MO - Ash	SI	Nitrate/Nitrite	0.1205	12	10	
MO - Ash	SI	Selenium	0.005	6	6	
MO - Ash and Coal Refuse	SI	Aluminum	296.2888026	19	6	
MO - Ash and Coal Refuse	SI	Arsenic	11.67554177	20	0	
MO - Ash and Coal Refuse	SI	Barium	0.039930301	20	1	
MO - Ash and Coal Refuse	SI	Boron	15.49313158	19	2	
MO - Ash and Coal Refuse	SI	Cadmium	0.124406392	27	9	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
MO - Ash and Coal Refuse	SI	Cobalt	4.8377	20	7	
MO - Ash and Coal Refuse	SI	Lead	0.321181411	20	11	
MO - Ash and Coal Refuse	SI	Molybdenum	0.402184211	19	15	
MO - Ash and Coal Refuse	SI	Nitrate/Nitrite	5.165	39	37	
MO - Ash and Coal Refuse	SI	Selenium	0.103823054	20	9	
O - Ash	SI	Arsenic	0.234766667	3	0	
O - Ash	SI	Boron	6.166666667	3	0	
O - Ash	SI	Molybdenum	0.0179	1	0	
O - Ash	SI	Nitrate/Nitrite	461	1	0	
O - Ash	SI	Selenium	0.0029	3	0	
OK - Ash	SI	Aluminum	40.45955556	9	0	
OK - Ash	SI	Arsenic	0.060628889	9	2	
OK - Ash	SI	Barium	0.159055556	9	1	
OK - Ash	SI	Boron	3.148333333	9	0	
OK - Ash	SI	Cadmium	0.01	9	9	
OK - Ash	SI	Lead	0.02	9	9	
OK - Ash	SI	Molybdenum	0.721694444	9	0	
OK - Ash	SI	Nitrate/Nitrite	7.62	18	17	
OK - Ash	SI	Selenium	0.282377778	9	2	
SX - Ash	SI	Aluminum	3.866609827	15	0	
SX - Ash	SI	Arsenic	0.054834273	15	2	
SX - Ash	SI	Barium	0.079191593	15	0	
SX - Ash	SI	Boron	32.70433889	15	0	
SX - Ash	SI	Cadmium	0.019243353	15	5	
SX - Ash	SI	Lead	0.001228153	15	5	
SX - Ash	SI	Molybdenum	11.40518778	15	0	
SX - Ash	SI	Nitrate/Nitrite	1.6328	30	12	
SX - Ash	SI	Selenium	0.239368793	15	6	

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Attachment A-3: CCW Constituent Data Used in Screening Analysis

Table A-3-1. CCW Landfill Waste Analyte Concentrations Used in Screening: Total Waste Analyses (mg/kg)

Analyte	Sites[1]	ND Sites[2]	2002 CCW Total Waste Concentrations						1998 Total Waste 95th
			Minimum	Maximum	50th	75th	90th	95th	
Aluminum	71	0	1.45E+01	1.37E+05	2.53E+04	4.17E+04	8.57E+04	9.76E+04	1.43E+05
Antimony	64	19	1.25E-01	3.10E+02	1.56E+01	2.94E+01	4.62E+01	7.93E+01	4.67E+01
Arsenic	111	3	4.70E-02	3.70E+02	2.79E+01	6.18E+01	1.05E+02	1.25E+02	1.54E+02
Barium	94	1	4.76E+00	7.14E+03	2.22E+02	4.49E+02	1.05E+03	2.59E+03	8.38E+03
Beryllium	37	6	1.19E-01	2.85E+01	4.10E+00	1.00E+01	1.76E+01	2.25E+01	1.56E+01
Boron	70	4	2.50E-02	2.47E+03	5.35E+01	1.50E+02	3.46E+02	5.54E+02	4.17E+02
Cadmium	102	21	1.65E-04	7.60E+02	1.08E+00	2.26E+00	5.43E+00	1.12E+01	2.37E+01
Chromium	108	2	5.00E-03	1.38E+03	4.45E+01	7.62E+01	1.66E+02	1.81E+02	2.91E+02
Cobalt	67	8	5.00E-03	1.35E+02	1.02E+01	3.26E+01	6.22E+01	7.93E+01	4.16E+01
Copper	95	3	5.00E-03	8.90E+02	3.61E+01	8.24E+01	2.28E+02	2.99E+02	1.55E+02
Cyanide	2	1	1.25E-01	2.48E-01	1.86E-01	2.17E-01	2.35E-01	2.41E-01	-
Fluoride	8	0	2.50E+00	7.61E+02	1.08E+01	2.07E+01	2.49E+02	5.05E+02	-
Lead	107	6	1.30E-02	1.37E+03	2.87E+01	4.97E+01	8.06E+01	1.25E+02	1.52E+02
Manganese	87	2	5.00E-02	9.81E+03	1.11E+02	2.41E+02	5.10E+02	6.37E+02	8.17E+02
Mercury	86	12	6.00E-04	6.43E+01	3.28E-01	6.00E-01	1.63E+00	8.22E+00	-
Molybdenum	73	7	4.43E-02	1.26E+02	1.20E+01	2.23E+01	3.47E+01	5.38E+01	4.31E+01
Nickel	106	5	4.90E-02	5.41E+04	4.23E+01	1.30E+02	3.29E+02	6.79E+02	1.55E+02
Nitrate	1	1	2.43E-01	2.43E-01	2.43E-01	2.43E-01	2.43E-01	2.43E-01	-
Nitrite	0	0	-	-	-	-	-	-	-
Selenium	94	11	5.05E-03	6.73E+02	5.12E+00	1.03E+01	2.14E+01	4.79E+01	3.24E+02
Silver	69	26	5.00E-02	1.90E+03	1.72E+00	3.30E+00	1.37E+01	2.66E+01	1.36E+01
Strontium	15	1	5.60E+00	1.23E+03	2.63E+02	7.63E+02	1.05E+03	1.20E+03	4.76E+03
Thallium	20	10	9.00E-02	1.00E+02	3.23E+00	1.05E+01	2.08E+01	4.21E+01	4.80E+01
Vanadium	43	1	3.30E+00	4.55E+03	2.24E+02	3.48E+02	9.07E+02	2.95E+03	3.46E+02
Zinc	98	1	3.40E-02	1.82E+04	4.58E+01	1.44E+02	2.93E+02	1.43E+03	8.56E+02

[1] Number of sites with analyte data (2002)

[2] Number of sites with only nondetect analyte data (2002)

Table A-3-2. CCW Surface Impoundment Waste Analyte Concentrations Used in Screening: Porewater Analyses (mg/L)

Analyte	Sites[1]	ND Sites[2]	2002 SI Porewater Concentrations						1998 Porewater 95th[3]
			Minimum	Maximum	50th	75th	90th	95th	
Aluminum	17	2	1.50E-02	8.91E+01	1.18E+00	4.68E+00	2.30E+01	5.02E+01	2.70E+02
Antimony	2	2	1.00E-02	7.00E-02	4.00E-02	5.50E-02	6.40E-02	6.70E-02	-
Arsenic	17	2	7.50E-03	6.77E+00	1.80E-01	4.94E-01	5.18E+00	5.65E+00	9.64E+00
Barium	17	2	1.00E-03	5.50E-01	1.10E-01	1.59E-01	3.02E-01	4.88E-01	2.74E+01
Beryllium	2	1	1.00E-03	6.20E-03	3.60E-03	4.90E-03	5.68E-03	5.94E-03	-
Boron	18	1	2.50E-02	3.37E+02	5.01E+00	2.92E+01	7.52E+01	1.44E+02	3.42E+02
Cadmium	17	9	1.00E-03	2.50E-01	2.50E-03	1.56E-02	1.31E-01	1.90E-01	1.56E-01
Chromium	18	8	9.00E-04	5.78E-01	3.56E-02	1.13E-01	3.66E-01	5.29E-01	7.46E-01
Cobalt	4	2	5.00E-03	8.87E+00	1.07E-01	2.37E+00	6.27E+00	7.57E+00	-
Copper	16	5	6.40E-04	7.22E-01	3.63E-02	1.26E-01	2.84E-01	4.90E-01	6.90E-01
Cyanide	0	0	-	-	-	-	-	-	-
Fluoride	15	2	5.05E-02	4.10E+02	8.96E-01	4.99E+00	1.91E+01	1.39E+02	4.10E+02
Lead	14	5	1.23E-03	2.28E-01	5.90E-03	4.53E-02	1.77E-01	2.16E-01	4.68E-01
Manganese	16	2	4.24E-03	1.82E+02	1.69E-01	1.20E+00	7.67E+00	5.15E+01	1.03E+02
Mercury	1	1	2.50E-04	2.50E-04	2.50E-04	2.50E-04	2.50E-04	2.50E-04	7.96E-04
Molybdenum	18	6	1.79E-02	1.14E+01	4.73E-01	6.55E-01	1.00E+00	2.70E+00	1.14E+01
Nickel	17	4	5.00E-03	1.23E+01	4.61E-02	2.75E-01	7.49E-01	3.09E+00	8.33E+00
Nitrate	13	3	8.05E-02	1.17E+03	1.85E+00	4.73E+00	6.02E+02	9.17E+02	1.17E+03
Nitrite	15	4	7.00E-03	4.61E+02	1.89E-01	1.39E+00	5.22E+00	1.43E+02	4.61E+02
Selenium	15	3	2.50E-03	1.03E+00	6.97E-02	1.93E-01	3.56E-01	5.92E-01	1.03E+00
Silver	8	8	5.00E-05	5.00E-03	2.06E-03	4.25E-03	5.00E-03	5.00E-03	
Strontium	17	0	4.20E-01	1.61E+01	4.25E+00	7.00E+00	8.74E+00	1.06E+01	1.61E+01
Thallium	2	2	2.50E-03	5.00E-02	2.63E-02	3.81E-02	4.53E-02	4.76E-02	
Vanadium	15	1	1.25E-03	6.61E-01	1.03E-01	3.15E-01	4.78E-01	5.81E-01	8.00E-01
Zinc	17	5	1.16E-02	2.34E+01	1.00E-01	1.20E-01	6.70E-01	5.40E+00	2.31E+01

[1] Number of sites with analyte data (2002)
[2] Number of sites with only nondetect analyte data (2002)
[3] Includes both landfill and surface impoundment (SI) porewater data

Table A-3-3. CCW Landfill Waste Analyte Concentrations Used in Screening: Leachate Analyses (mg/L)

Analyte	Sites[1]	ND Sites[2]	Leachate Concentrations						1998 TCLP 95th
			Minimum	Maximum	50th	75th	90th	95th	
Aluminum	54	3	3.00E-02	2.86E+01	2.06E+00	4.47E+00	1.05E+01	1.36E+01	-
Antimony	60	27	6.50E-04	7.87E-01	2.19E-02	7.50E-02	2.61E-01	2.98E-01	-
Arsenic	119	26	1.00E-03	1.80E+00	3.65E-02	1.31E-01	3.94E-01	1.01E+00	2.40E-01
Barium	115	7	2.00E-02	4.20E+01	3.04E-01	5.71E-01	1.60E+00	2.55E+00	-
Beryllium	47	15	5.00E-05	2.80E-01	2.14E-03	5.37E-03	1.58E-02	2.96E-02	-
Boron	72	3	1.00E-02	2.79E+01	1.07E+00	4.57E+00	1.06E+01	2.07E+01	-
Cadmium	117	38	1.50E-04	6.00E-01	1.00E-02	2.24E-02	4.94E-02	9.00E-02	-
Chromium	118	17	1.00E-03	7.64E-01	3.40E-02	1.00E-01	2.00E-01	3.50E-01	5.90E-02
Cobalt	51	10	1.92E-03	2.46E-01	1.52E-02	2.55E-02	8.25E-02	1.31E-01	-
Copper	72	13	1.60E-03	3.27E+00	4.14E-02	9.46E-02	1.50E-01	4.55E-01	-
Cyanide	24	14	3.50E-03	1.20E-01	7.23E-03	2.03E-02	6.32E-02	8.67E-02	-
Fluoride	33	1	8.00E-02	5.99E+01	8.19E-01	1.90E+00	6.34E+00	3.09E+01	-
Lead	116	38	1.00E-03	3.61E+00	3.23E-02	7.23E-02	2.39E-01	2.90E-01	-
Manganese	72	13	1.25E-03	3.27E+00	1.63E-01	4.39E-01	1.37E+00	1.56E+00	-
Mercury	97	60	5.00E-06	2.90E-01	2.89E-04	1.00E-03	2.69E-03	1.32E-02	-
Molybdenum	49	5	1.00E-02	3.09E+01	1.77E-01	3.40E-01	6.16E-01	1.27E+00	-
Nickel	80	19	2.00E-03	3.88E+00	5.17E-02	1.41E-01	3.09E-01	5.70E-01	5.00E-02
Nitrate	17	3	1.75E-02	2.60E+01	1.59E+00	2.50E+00	2.83E+00	7.72E+00	-
Nitrite	5	4	5.00E-02	5.00E+00	8.33E-01	1.17E+00	3.47E+00	4.23E+00	-
Selenium	119	23	1.00E-03	1.05E+00	4.87E-02	8.74E-02	1.76E-01	2.06E-01	4.40E-01
Silver	109	60	0.00E+00	2.50E-01	8.70E-03	1.75E-02	3.95E-02	5.02E-02	-
Strontium	20	0	6.35E-02	4.28E+01	2.95E+00	4.87E+00	9.70E+00	1.36E+01	-
Thallium	40	18	1.00E-03	1.97E-01	8.29E-03	2.34E-02	5.00E-02	6.54E-02	-
Vanadium	40	5	1.00E-03	1.20E+01	1.07E-01	1.82E-01	4.50E-01	1.50E+00	-
Zinc	75	9	2.00E-03	5.83E+01	1.30E-01	6.09E-01	1.94E+00	1.01E+01	-

[1] Number of sites with analyte data (2002)
[2] Number of sites with only nondetect analyte data (2002)
TCLP = Toxicity Characteristic Leaching Procedure

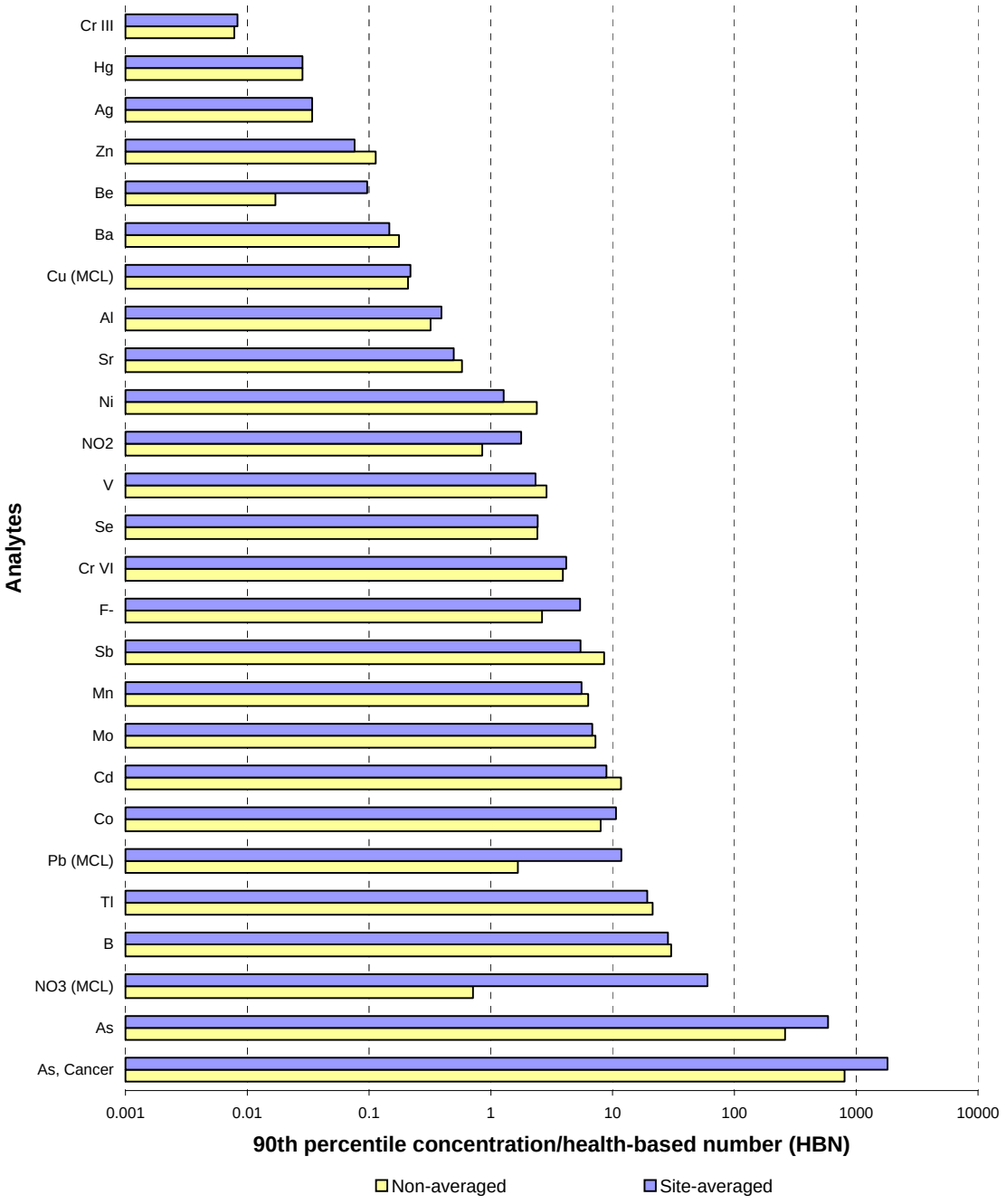

Figure A-3-1. Comparison of site-averaged and nonaveraged results for surface impoundment porewater screening, groundwater-to-drinking-water pathway.

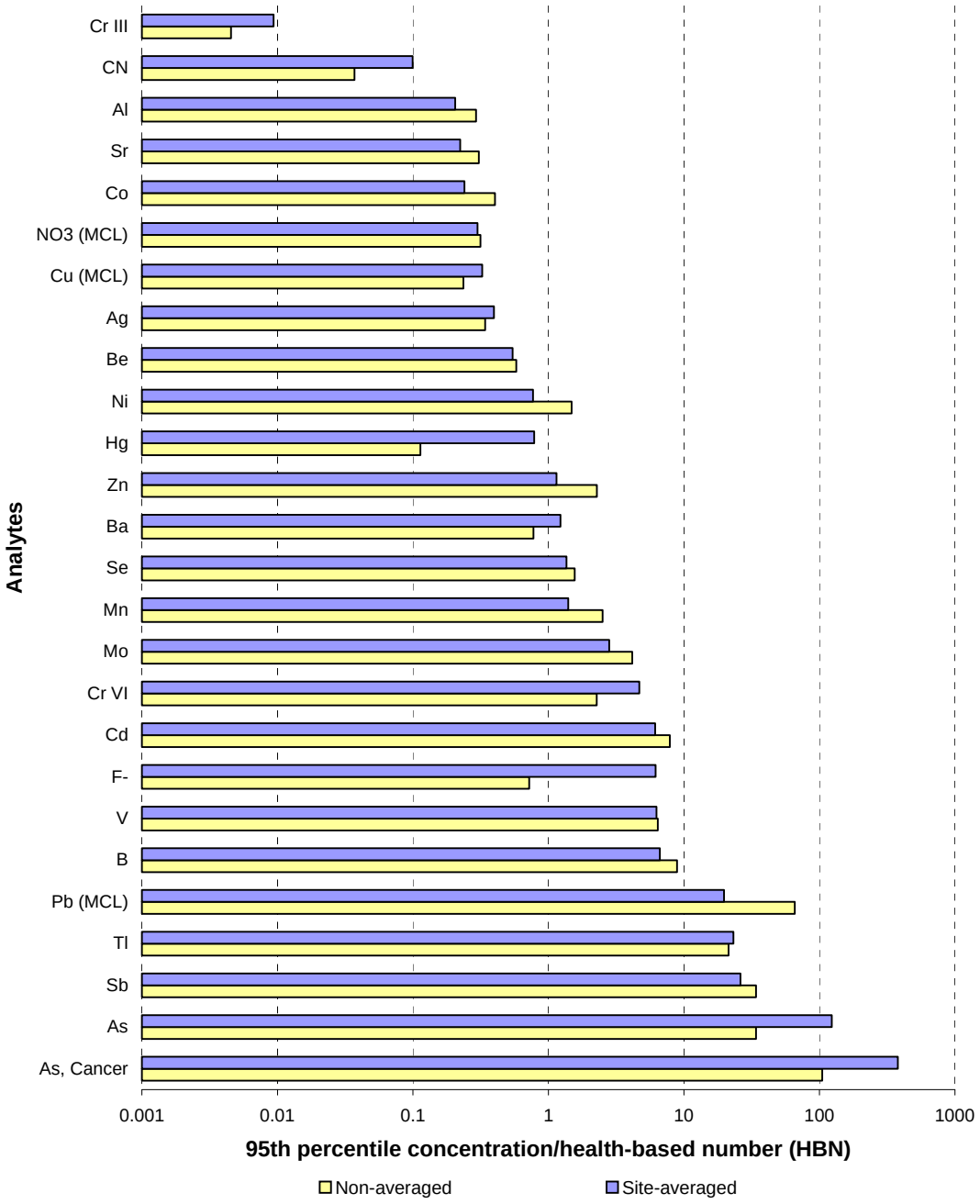

Figure A-3-2. Comparison of site-averaged and nonaveraged results for landfill leachate screening, groundwater-to-drinking-water pathway.

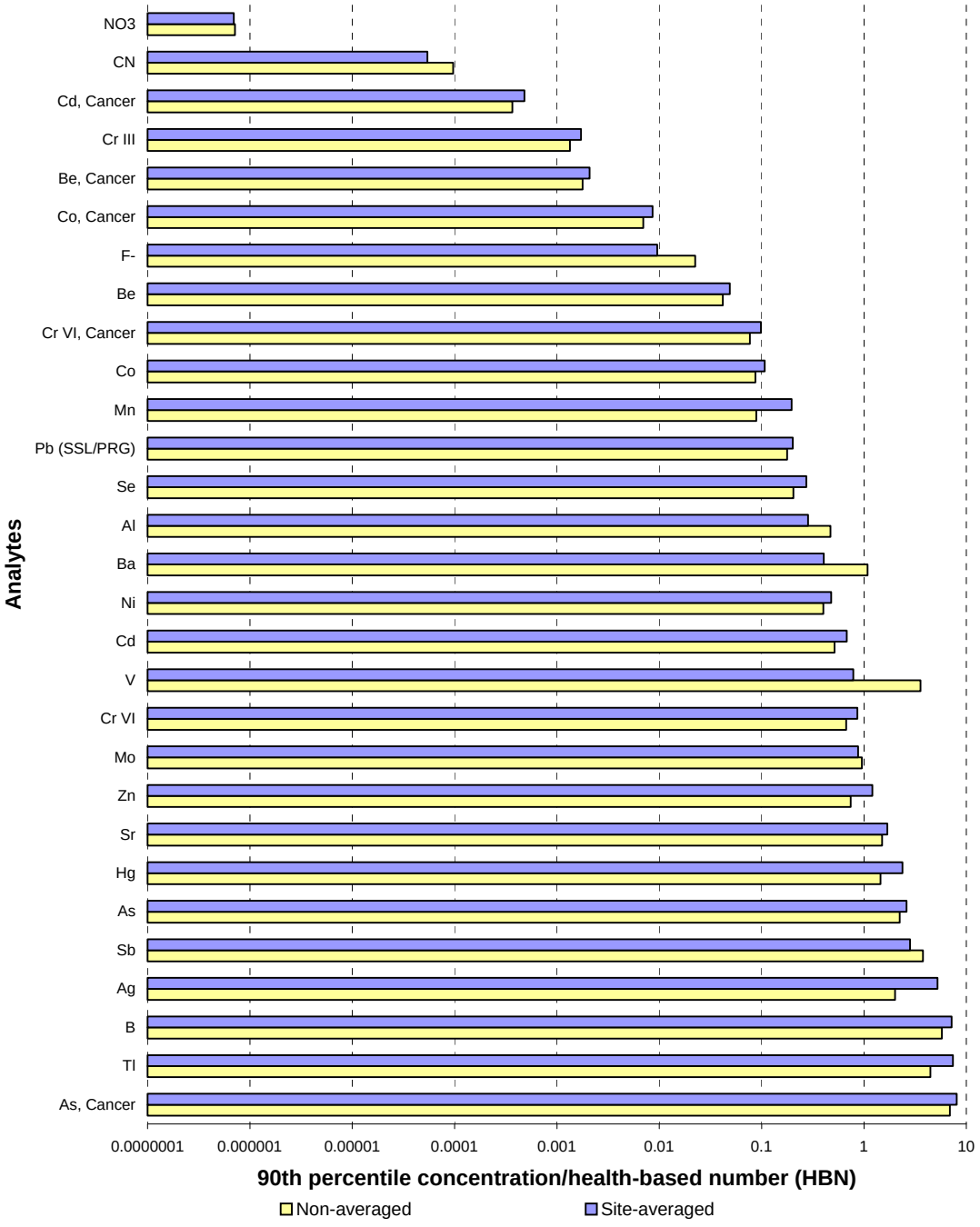

Figure A-3-3. Comparison of site-averaged and nonaveraged results for landfill total waste screening, aboveground pathways.

Appendix B. Waste Management Units

The source models supporting the CCW risk assessment require inputs describing the characteristics of CCW waste management units (WMUs). To satisfy this requirement, the assessment used a data set of WMU area, capacity, liner type, geometry, and waste type managed for a set of individual CCW landfills and surface impoundments that are representative of the national population of coal combustion facilities that are managing their wastes onsite.

The sources for these data sets were responses to two voluntary industry surveys: an Electric Power Research Institute (EPRI) comanagement survey (for conventional utility coal combustion WMUs units) and a Council of Industrial Boiler Owners (CIBO) fluidized bed combustion (FBC) survey (for FBC WMUs). In addition to the individual WMU data, certain assumptions were required regarding (1) liner types and characteristics, (2) surface impoundment operating life, and (3) above- and below-grade geometries for WMUs. The sections below describe the two industry surveys, then discuss the data sources and assumptions made. **Attachment B-1** lists the 181 CCW disposal sites modeled in this risk assessment and their locations. **Attachment B-2** presents the WMU data used in the CCW risk assessment for each of the 108 landfills and 96 surface impoundments at these coal combustion facilities.

B.1 EPRI Comanagement Survey

For conventional utility coal combustion WMUs, the source of data for area, capacity, liner type, and waste type managed was the EPRI Coal Combustion By-Products and Low-Volume Wastes Comanagement Survey (EPRI, 1997a). In 1995, EPRI sent a 4-page questionnaire to all electric utilities with more than 100 megawatts (MW) of coal-fired generating capacity. The survey gathered data on the design of coal combustion management units and the types and volumes of waste managed. From the survey responses, EPRI prepared an electronic database and provided it to EPA in support of the March 1999 *Report to Congress: Wastes from the Combustion of Fossil Fuels* (the RTC) (U.S. EPA, 1999a). EPRI also published a report (EPRI, 1997a) documenting the survey format and providing a brief summary of the results.

The EPRI survey responses include information on 323 waste management facilities serving 238 power plants located in 36 states. The total annual volume of CCW reported disposed by respondents to the EPRI comanagement survey was nearly 62 million tons. This quantity was two-thirds of the total generation of CCW in 1995. Therefore, the survey sample encompasses the majority of CCW disposed in terms of volume. Based on comparison with data from other sources, the EPRI survey sample appears representative of the population of coal combustion WMUs in terms of the types of units included (i.e., landfills and surface impoundments). The EPRI survey sample also is believed to be generally geographically representative of the population of conventional utility WMUs, although it may under-represent certain management practices in a few states. The EPA document, *Technical Background Document for the Supplemental Report to Congress on Remaining Fossil Fuel Combustion*

Wastes: Industry Statistics and Waste Management Practices (U.S. EPA, 1999b), discusses the representativeness of the EPRI survey in greater detail and provides extensive summary statistics on the survey responses.

The EPRI comanagement survey included questions requesting the respondent to report the location of the WMU (by state) and the WMU area, capacity, liner type, and waste type managed. Therefore, the data set used for modeling these variables was extracted directly from the EPRI database for all active landfills and surface impoundments responding to the EPRI survey. Mine placement sites and closed WMUs were excluded from the data set. Also excluded from the data set were three responding WMUs that managed FBC waste. Data for these units were instead combined with the data set for FBC WMUs from the CIBO FBC survey (described below).

The EPRI survey data were provided in blinded form. That is, the original database did not report the identity of each respondent and identified WMU location only by state. To provide a more complete identification of the EPRI waste management locations, each unit in the EPRI database had to be matched with a specific electric utility facility. This matching was accomplished by applying professional judgment in comparing the state, waste quantity, and waste management practice information in the EPRI database with similar data from responses to the U.S. Department of Energy's Energy Information Administration (EIA) Form EIA-767 (Steam-Electric Plant Operation and Design Report) for the same year as the EPRI survey (1995). The latitude and longitude plant locations in the EIA database allowed the pairing of the EPRI WMU data with environmental setting information.

B.2 CIBO Fluidized Bed Combustion Survey

For FBC WMUs, the primary source of data for area, capacity, liner type, and waste type managed was the CIBO Fossil Fuel Fluidized Bed Combustion (FBC) Survey. In 1996, CIBO sent a voluntary questionnaire to every fossil-fuel-fired FBC plant, both utility and nonutility, in the United States. This survey collected general facility information, characterized process inputs and outputs, gathered data on waste generation and characteristics, and captured details of FBC waste management practices. From the survey responses, CIBO prepared an electronic database and provided it to EPA in support of the March 1999 RTC. CIBO also published a report (CIBO, 1997) that includes documentation of the survey format and provides a brief summary of the results.

CIBO reports a total of 84 facilities using FBC technology. Forty-five of these responded to the CIBO FBC survey, with 20 of the respondents providing information about waste management practices. The facilities with waste management data cover 24 percent of all U.S. facilities using FBC. The CIBO sample is geographically representative of the full population, with the exception of two states that appear under-represented in the sample—Pennsylvania and Illinois. EPA's technical background document on industry statistics and waste management practices (U.S. EPA, 1999b) discusses the representativeness of the EPRI survey in greater detail and provides extensive summary statistics on the survey responses.

The CIBO survey includes questions requesting the respondent to report WMU area, capacity, liner type, and waste type managed. Therefore, the data set used for modeling these

variables was extracted directly from the CIBO database. The CIBO respondents included both utility and nonutility (i.e., industrial or institutional facilities that burn coal, but are not primarily engaged in the business of selling electricity) facilities. Because nonutilities are outside the scope of this risk assessment, nonutilities were excluded from the data set. Three additional utility facilities were excluded from the data set because their responses contained insufficient data on the variables of interest (area, capacity, liner type, and waste type). Mine placement sites also were excluded from the data set. Data for the FBC units responding to the EPRI survey (see **Section B.1**) were added to the data set. This resulted in a sample of seven FBC landfills and one FBC surface impoundment for modeling. **Table B-1** compares this sample to the waste management practices of the full utility FBC population.

As shown in Table B-1, FBC facilities frequently avoid waste disposal units by directing all of their waste to mine placement or beneficial use. Therefore, although only 8 of the 41 utility FBC facilities were included in the model data set, these 8 facilities represent nearly all of the known FBC landfills and surface impoundments.

Table B-1. Utility FBC Waste Management Practices and Units Modeled

Number of Facilities...	Total	Landfill	Surface Impoundment	Minefill or Beneficial Use	Unknown
in the full population	41	11	1	16	13
modeled	8	7	1	Not applicable	Not applicable

The CIBO survey database identified the location of each WMU in detail (latitude and longitude). Therefore, no additional analysis was necessary to pair the WMU data with environmental setting information.

B.3 Liner Type

The EPRI survey data included information on the liner (if any) for each WMU. For this assessment, the WMUs were assigned to one of three liner scenarios based on the EPRI liner data: an unlined (no liner) scenario, a compacted clay liner, and a composite liner that combines a plastic (e.g., high-density polyethylene (HDPE) membrane) over either geosynthetic or natural clays. These three scenarios correspond to the following conceptual liner scenarios, developed in support of EPA's Industrial Subtitle D guidance (U.S. EPA, 2002), which can be selected in the landfill and surface impoundment models used in this assessment.

- **Unlined Scenario.** For landfills, waste is placed directly on local soils, either on grade or excavated to some design depth and without a leachate collection system. After the landfill has been filled to capacity, a 2-foot native soil cover (the minimum required by Subtitle D regulations) is installed and assumed to support vegetation. For surface impoundments, wastewater is placed directly on local soils, and the depth of water is constant over the entire life of the impoundment, pre- and post-closure. Sediments accumulate and consolidate at the bottom of the impoundment and migrate into the underlying native soils, where they clog pore spaces and provide some barrier to flow.

- **Clay Liner Scenario.** For landfills, waste is placed directly on a 3-foot compacted clay liner, which is installed on the local soils, either on grade or excavated to some design depth and without a leachate collection system. After the landfill has been filled to capacity, a 3-foot clay cover is installed and covered with 1 foot of loam to support vegetation and drainage. The hydraulic conductivity of both the liner and cover clays is assumed to be $1x10^{-7}$ cm/sec. For surface impoundments, wastewater is placed on a compacted clay liner, which is installed on the local soils. The assumptions for an unlined impoundment also apply to the compacted clay liner scenario, except that a compacted clay liner filters out the sediments that clog the native soils in the unlined case, so the effect of clogging the native materials is not included in the calculation of the infiltration rate. The thickness of the compacted clay liner was assumed to be 3 feet and the hydraulic conductivity was assumed to be $1x10^{-7}$ cm/sec.

- **Composite Liner Scenario.** For landfills, wastes are placed on a liner system that consists of a 60 mil HDPE membrane with either an underlying geosynthetic clay liner with a maximum hydraulic conductivity of $5x10^{-9}$ cm/sec, or a 3-foot compacted clay liner with a maximum hydraulic conductivity of $1x10^{-7}$ cm/sec. A leachate collection system is also assumed to exist between the waste and the liner system. After the landfill has been filled to capacity, a 3-foot clay cover is assumed to be installed and covered with 1 foot of loam to support vegetation and drainage. For surface impoundments, wastewater is placed on a synthetic membrane with an underlying geosynthetic or natural compacted clay liner with a hydraulic conductivity of $1x10^{-7}$ cm/sec. The membrane liner was assumed to have a number of pinhole leaks of uniform size (6 mm^2). The number of these leaks was based on an empirical distribution of membrane leak density values obtained from TetraTech (2001), as described in the *IWEM Technical Background Document* (U.S. EPA, 2002).

Table B-2 shows the crosswalk used to assign one of the three liner scenarios to each facility based on the liner data in the EPRI survey data (EPRI, 1997a). **Attachment B-2** provides these assignments, along with the original EPRI liner type, for each CCW landfill facility modeled.

Table B-2. Crosswalk Between EPRI and CCW Source Model Liner Types

EPRI Liner Type	Model Liner Code	Description
Compacted ash	0	no liner
Compacted clay	1	clay
Composite clay/membrane	2	composite
Double	2	composite
Geosynthetic membrane	2	composite
None/natural soils	0	no liner

B.4 Surface Impoundment Operating Life

The model runs for surface impoundments required a general assumption about the length of the operating life for these WMUs. Of the surface impoundments in the EPRI comanagement survey, 86 provided responses to questions about both the unit's opening date and expected closure date. From these two dates, an expected operating life for each impoundment could be calculated. An additional 30 impoundments provided an opening date, but no closure date. One possible interpretation of these responses is that these facilities do not expect to close in the foreseeable future, corresponding to a very long or indefinite operating life with dredging of waste to maintain capacity. **Figure B-1** shows the distribution of the calculated operating lives, along with a bar showing the facilities with no closure date.

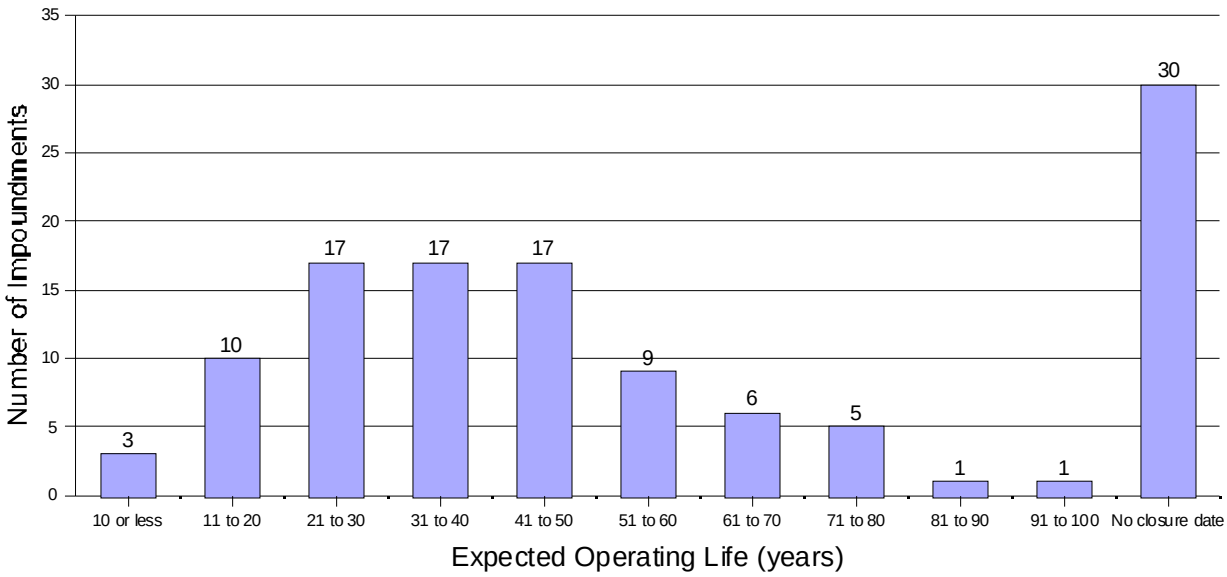

Figure B-1. Operating life of impoundments in the EPRI survey.

Based on these data, a 75-year operating life was chosen. This value corresponds to the 95th percentile of the observed distribution. While the use of a 95th percentile value may appear conservative, if many of the facilities with no closure date do, in fact, plan to operate indefinitely, 75 years would correspond to a much lower percentile in the distribution. More significantly, many CCW surface impoundments close with wastes in place. The selection of 75 years minimizes the underestimation of chronic risks for this scenario, given that EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP) surface impoundment model assumes clean closure after the operating life.

B.5 Above- and Below-Grade Geometry

The model runs for surface impoundments and landfills required general assumptions about the geometry of these units with respect to the ground surface (i.e., how much of the unit's depth is below grade). The CIBO FBC survey included data on this geometry, so, for FBC units, these data were extracted directly from the database along with the other individual WMU data

(e.g., capacity). The EPRI comanagement survey did not contain data describing above- and below-grade geometry. Therefore, for conventional utility coal combustion WMUs, EPA reviewed 17 site-characterization reports published by EPRI (EPRI 1991; 1992; 1994a,b; 1996a,b; 1997b-k) and determined an above- versus below-grade geometry for each unit described in those reports based on schematic diagrams and site descriptions. EPA also extracted data from another CIBO voluntary survey that covered conventional (non-FBC) nonutility coal combustors. **Figures B-2** and **B-3** display the distributions of the data thus collected.

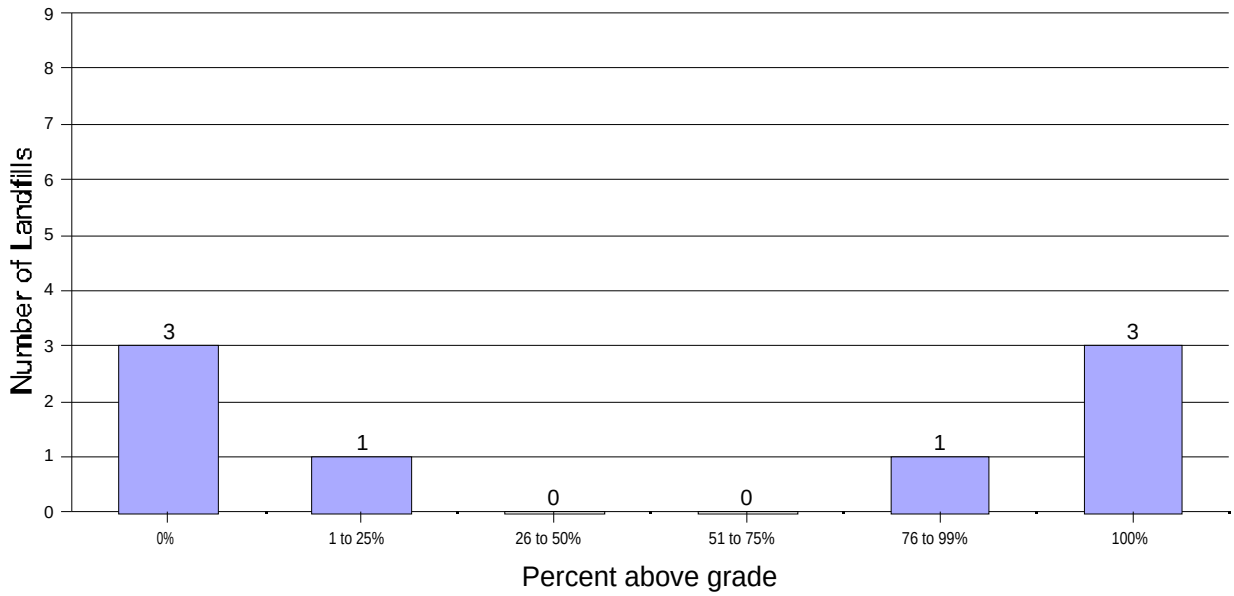

Figure B-2. Above- and below-grade geometry for landfills.

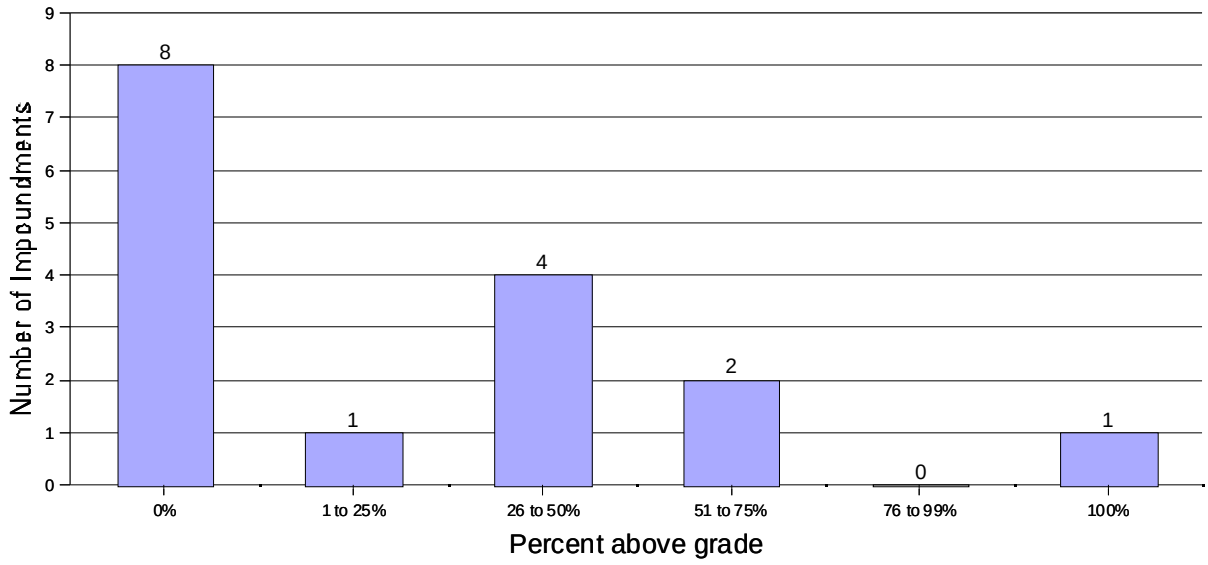

Figure B-3. Above- and below-grade geometry for impoundments.

For landfills, because the data were limited (8 sites), the model runs assumed that the percent below grade ranged from 1 to 100 and was uniformly distributed. For each landfill iteration, a random value for percent below grade was picked and applied to the landfill depth to determine depth below ground surface. This value was constrained to be no deeper than the water table and was checked to see that EPACMTP groundwater mounding constraints were not violated.

For surface impoundments, more data were available (16 sites), with 8 sites being constructed entirely below grade and the remaining 8 sites ranging from 7.5 to 45 feet above grade. For each surface impoundment iteration, height above grade at these 15 sites was randomly sampled as an empirical distribution and applied to the overall surface impoundment depth to determine depth below ground surface.

B.6 Calculation of WMU Depth and Imputation of Missing WMU Data

The EPRI survey includes information on the total area and total waste capacity of each landfill and surface impoundment included in the survey. To calculate average depth for each WMU (a necessary EPACMTP model input), the total waste capacity was divided by the area. The resulting depths were then checked for reasonableness. For surface impoundments, one depth (1 foot) was culled as being unrealistically low and one (700 feet) as too high. Two landfill depths less than 2 feet and one depth greater than 350 feet were also removed from the database. In these cases the EPRI waste capacity data were culled and replaced using the regressions described below (i.e., WMU areas are considered more reliable than the capacity estimates in the survey data), and new capacities were estimated as described below.

In addition, four landfills and six surface impoundments had neither area nor capacity data in the EPRI survey. In these cases, the EIA facility locations were used to find the plants and their WMUs on aerial photos from the Terraserver Web site (http://terraserver-usa.com/geographic.aspx), and a geographic information system (GIS) was used to measure the areas of the units in question. Capacities were then estimated as described below.

To impute data for facilities missing either area or capacity data in the EPRI survey, linear regression equations were developed based on WMUs with both area and capacity data, one to predict area from capacity, and one to predict capacity from area. The final regression equations are shown in **Figures B-4** and **B-5** for landfills and **Figures B-6** and **B-7** for surface impoundments. In each case, a standard deviation around the regression line was also computed and used during source data file preparation to randomly vary the area or capacity from iteration to iteration within the bounds of the existing data set.

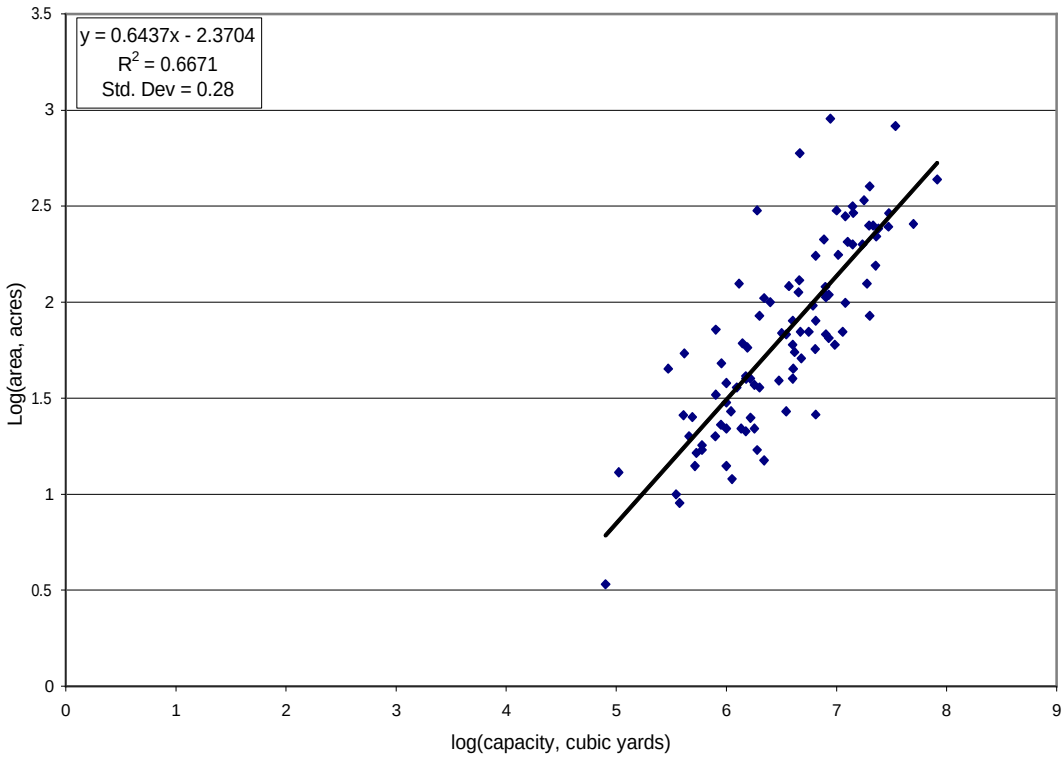

Figure B-4. Linear regression to impute landfill area from capacity.

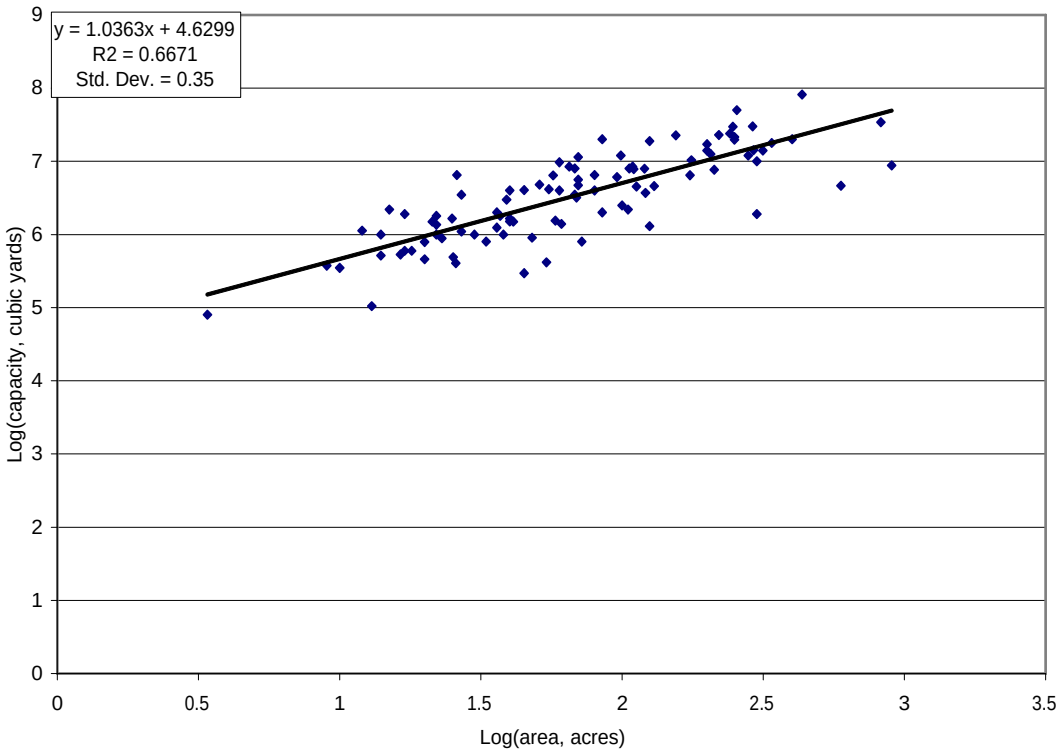

Figure B-5. Linear regression to impute landfill capacity from area.

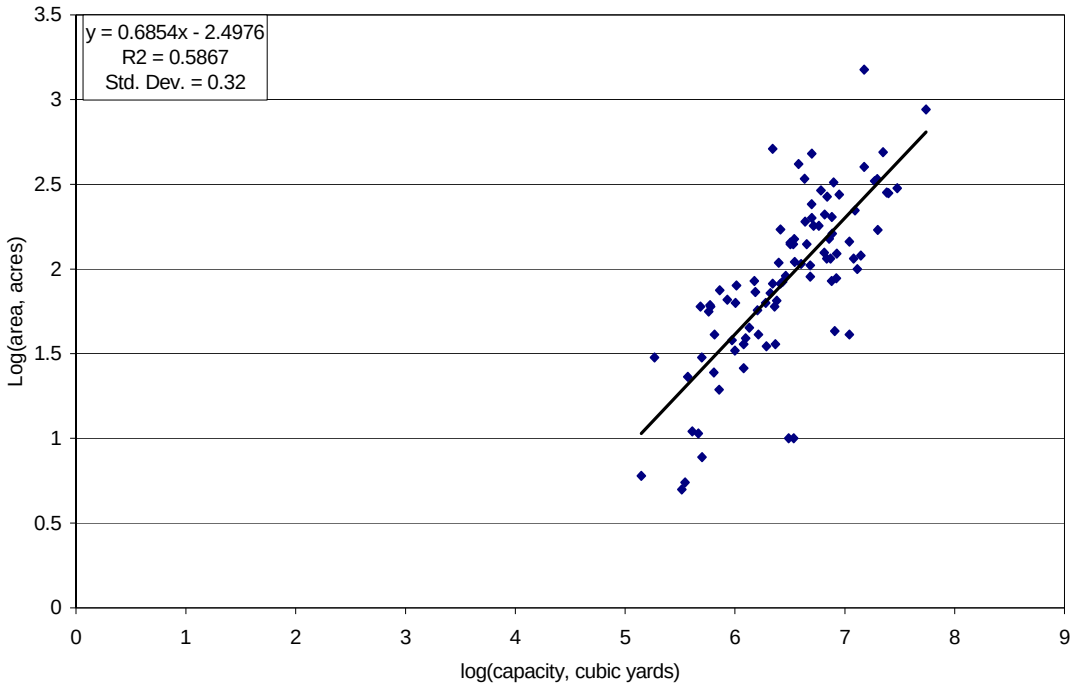

Figure B-6. Linear regression to impute surface impoundment area from capacity.

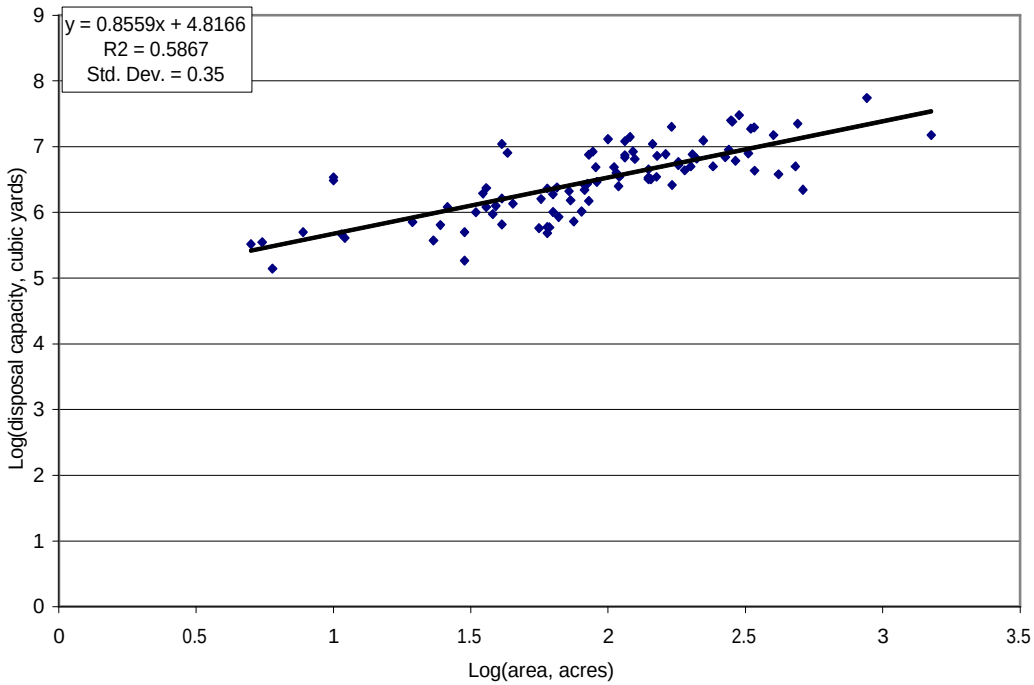

Figure B-7. Linear regression to impute surface impoundment capacity from area.

B.7 Results

Attachment B-1 lists the 181 CCW disposal sites modeled in this risk assessment and their locations. The WMU data used in the CCW risk assessment for each of the 108 landfills and 96 surface impoundments at these coal combustion facilities are presented in **Attachment B-2**. Missing data that were randomly replaced as described above are not represented in the table (i.e., the fields are left blank).

B.8 References

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U.S. EPA (Environmental Protection Agency). 2002. *Industrial Waste Management Evaluation Model (IWEM) Technical Background Document*. EPA 530-R-02-012. Office of Solid Waste, Washington, DC. August.

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Attachment B-1: CCW Disposal Sites (Plants)

Plant Name	Utility Name	County	State	Latitude	Longitude
A B Brown	Southern Indiana Gas & Elec. Co.	Posey	IN	37.9053	87.715
A/C Power - Ace Operations	A.C.E. Cogeneration Co.	San Bernardino	CA	35.75	117.3667
Allen	Tennessee Valley Authority	Shelby	TN	35.0742	90.1492
Alma	Dairyland Power Coop	Buffalo	WI	44.3078	91.905
Antelope Valley	Basin Electric Power Coop	Mercer	ND	47.37	101.8353
Arkwright	Georgia Power Co.	Bibb	GA	32.9269	83.6997
Asheville	Carolina Power & Light Co.	Buncombe	NC	35.4714	82.5431
Baldwin	Illinois Power Co.	Randolph	IL	38.205	89.8544
Barry	Alabama Power Co.	Mobile	AL	31.0069	88.0103
Bay Front	Northern States Power Co.	Ashland	WI	43.4833	89.4
Bay Shore	Toledo Edison Co.	Lucas	OH	41.6925	83.4375
Belews Creek	Duke Power Co.	Stokes	NC	36.2811	80.0603
Ben French	Black Hills Corp.	Pennington	SD	44.0872	103.2614
Big Cajun 2	Cajun Electric Power Coop, Inc.	Pointe Coupee	LA	30.7283	91.3686
Big Sandy	Kentucky Power Co.	Lawrence	KY	38.1686	82.6208
Big Stone	Otter Tail Power Co.	Grant	SD	45.3047	96.5083
Black Dog Steam Plant	Northern States Power Company	Dakota	MN	44.8167	93.25
Blue Valley	Independence, City of	Jackson	MO	39.0919	94.3364
Bowen	Georgia Power Co.	Bartow	GA	34.1256	84.9192
Brandon Shores	Baltimore Gas & Electric Co.	Anne Arundel	MD	39.18	76.5333
Buck	Duke Power Co.	Rowan	NC	35.7133	80.3767
Bull Run	Tennessee Valley Authority	Anderson	TN	36.0211	84.1567
C D McIntosh Jr.	Lakeland, City of	Polk	FL	28.075	81.9292
C P Crane	Baltimore Gas & Electric Co.	Baltimore City	MD	39.2845	76.6207
Cape Fear	Carolina Power & Light Co.	Chatham	NC	35.5989	79.0492
Carbon	PacifiCorp	Carbon	UT	39.7264	110.8639
Cardinal	Cardinal Operating Co.	Jefferson	OH	40.2522	80.6486
Cayuga	PSI Energy, Inc.	Vermillion	IN	39.9008	87.4136
Chalk Point	Potomac Electric Power Co.	Prince Georges	MD	38.5639	76.6806
Cholla	Arizona Public Service Co.	Navajo	AZ	34.9414	110.3003
Cliffside	Duke Power Co.	Cleveland	NC	35.22	81.7594
Clover	Virginia Electric & Power Co.	Halifax	VA	36.8667	78.7
Coal Creek	Coop Power Assn.	McLean	ND	47.3789	101.1572
Coleto Creek	Central Power & Light Co.	Goliad	TX	28.7128	97.2142

(continued)

CCW Disposal Sites (Plants) (continued)

Plant Name	Utility Name	County	State	Latitude	Longitude
Colstrip	Montana Power Co.	Rosebud	MT	45.8844	106.6139
Conemaugh	GPU Service Corporation	Indiana	PA	40.3842	79.0611
Conesville	Columbus Southern Power Co.	Coshocton	OH	40.1842	81.8811
Council Bluffs	MidAmerican Energy Co.	Pottawattamie	IA	41.18	95.8408
Crawford	Commonwealth Edison Co.	Cook	IL	39.8225	90.5681
Crist	Gulf Power Co.	Escambia	FL	30.5658	87.2239
Cross	South Carolina Pub Serv. Auth.	Berkeley	SC	33.3694	80.1119
Cumberland	Tennessee Valley Authority	Stewart	TN	36.3942	87.6539
Dale	East Kentucky Power Coop, Inc.	Clark	KY	37.875	84.25
Dallman	Springfield, City of	Sangamon	IL	39.7547	89.6008
Dan E Karn	Consumers Energy Co.	Bay	MI	43.645	83.8414
Dan River	Duke Power Co.	Rockingham	NC	36.4861	79.7244
Danskammer	Central Hudson Gas & Elec. Corp.	Orange	NY	41.5719	73.9664
Dave Johnston	PacifiCorp	Converse	WY	42.8333	105.7667
Dickerson	Potomac Electric Power Co.	Montgomery	MD	39.144	77.2059
Dolet Hills	CLECO Corporation	De Soto	LA	32.0308	93.5644
Duck Creek	Central Illinois Light Co.	Fulton	IL	40.4644	89.9825
Dunkirk	Niagara Mohawk Power Corp.	Chautauqua	NY	42.4919	79.3469
E D Edwards	Central Illinois Light Co.	Peoria	IL	40.5961	89.6633
E W Brown	Kentucky Utilities Co.	Mercer	KY	37.7911	84.7147
Eckert Station	Lansing, City of	Ingham	MI	42.7189	84.5583
Edgewater	Wisconsin Power & Light Co.	Sheboygan	WI	43.7181	87.7092
Elmer W Stout	Indianapolis Power & Light Co.	Marion	IN	39.7122	86.1975
F B Culley	Southern Indiana Gas & Elec. Co.	Warrick	IN	37.91	87.3267
Fayette Power Prj.	Lower Colorado River Authority	Fayette	TX	29.9172	96.7506
Flint Creek	Southwestern Electric Power Co.	Benton	AR	36.2625	94.5208
Fort Martin	Monongahela Power Co.	Monongalia	WV	39.7	79.9167
Frank E Ratts	Hoosier Energy R E C, Inc.	Pike	IN	38.5186	87.2725
G G Allen	Duke Power Co.	Gaston	NC	35.1897	81.0122
Gadsden	Alabama Power Co.	Etowah	AL	34.0136	85.9703
Gallatin	Tennessee Valley Authority	Sumner	TN	36.3156	86.4006
Gen J M Gavin	Ohio Power Co.	Gallia	OH	38.9358	82.1164
Genoa	Dairyland Power Coop	Vernon	WI	43.5592	91.2333
Gibson	PSI Energy, Inc.	Gibson	IN	38.3589	87.7783
Gorgas	Alabama Power Co.	Walker	AL	33.5111	87.235
Green River	Kentucky Utilities Co.	Muhlenberg	KY	37.3636	87.1214
Greene County	Alabama Power Co.	Greene	AL	32.6	87.7667
H B Robinson	Carolina Power & Light Co.	Darlington	SC	34.4	80.1667
Hammond	Georgia Power Co.	Floyd	GA	34.3333	85.2336

(continued)

CCW Disposal Sites (Plants) (continued)

Plant Name	Utility Name	County	State	Latitude	Longitude
Harllee Branch	Georgia Power Co.	Putnam	GA	33.1942	83.2994
Harrison	Monongahela Power Co.	Harrison	WV	39.3833	80.3167
Hatfield's Ferry	West Penn Power Co.	Greene	PA	39.85	79.9167
Hennepin	Illinois Power Co.	Putnam	IL	41.3028	89.315
Heskett	Montana-Dakota Utilities Co.	Morton	ND	46.8669	100.8839
Holcomb	Sunflower Electric Power Corp.	Finney	KS	37.9319	100.9719
Homer City	GPU Service Corporation	Indiana	PA	40.5142	79.1969
Hoot Lake	Otter Tail Power Co.	Otter Tail	MN	46.29	96.0428
Hugo	Western Farmers Elec. Coop, Inc.	Choctaw	OK	34.0292	95.3167
Hunter	PacifiCorp	Emery	UT	39.1667	111.0261
Huntington	PacifiCorp	Emery	UT	39.3792	111.075
Intermountain	Los Angeles, City of	Millard	UT	39.5108	112.5792
J H Campbell	Consumers Energy Co.	Ottawa	MI	42.9103	86.2031
J M Stuart	Dayton Power & Light Co.	Adams	OH	38.6364	83.7422
J R Whiting	Consumers Energy Co.	Monroe	MI	41.7914	83.4486
Jack McDonough	Georgia Power Co.	Cobb	GA	33.8244	84.475
Jack Watson	Mississippi Power Co.	Harrison	MS	30.4392	89.0264
James H Miller Jr.	Alabama Power Co.	Jefferson	AL	33.6319	87.0597
Jim Bridger	PacifiCorp	Sweetwater	WY	41.75	108.8
John E Amos	Appalachian Power Co.	Putnam	WV	38.4731	81.8233
John Sevier	Tennessee Valley Authority	Hawkins	TN	36.3767	82.9639
Johnsonville	Tennessee Valley Authority	Humphreys	TN	36.0278	87.9861
Joliet 29	Commonwealth Edison Co.	Will	IL	41.4892	88.0844
Keystone	GPU Service Corporation	Armstrong	PA	40.6522	79.3425
Killen Station	Dayton Power & Light Co.	Adams	OH	38.6903	83.4803
Kingston	Tennessee Valley Authority	Roane	TN	35.8992	84.5194
Kraft	Savannah Electric & Power Co	Chatham	GA	32.1333	81.1333
L V Sutton	Carolina Power & Light Co.	New Hanover	NC	34.2831	77.9867
Lansing	Interstate Power Co.	Allamakee	IA	43.3386	91.1667
Laramie R Station	Basin Electric Power Coop	Platte	WY	42.1086	104.8711
Lawrence EC	KPL Western Resources Co.	Douglas	KS	39.0078	95.2681
Lee	Carolina Power & Light Co.	Wayne	NC	35.3778	78.1
Leland Olds	Basin Electric Power Coop	Mercer	ND	47.2833	101.4
Lon Wright	Fremont, City of	Dodge	NE	41.45	96.5167
Louisa	MidAmerican Energy Co.	Louisa	IA	41.3181	91.0931
Marion	Southern Illinois Power Coop	Williamson	IL	37.6167	88.95
Marshall	Duke Power Co.	Catawba	NC	35.5975	80.9658
Martin Lake	Texas Utilities Electric Co.	Rusk	TX	32.2606	94.5708
Mayo	Carolina Power & Light Co.	Person	NC	36.5278	78.8919
Meramec	Union Electric Co.	St Louis	MO	38.6522	90.2397

(continued)

CCW Disposal Sites (Plants) (continued)

Plant Name	Utility Name	County	State	Latitude	Longitude
Merom	Hoosier Energy R E C, Inc.	Sullivan	IN	39.0694	87.5108
Miami Fort	Cincinnati Gas & Electric Co.	Hamilton	OH	39.1111	84.8042
Milton R Young	Minnkota Power Coop, Inc.	Oliver	ND	47.0664	101.2139
Mitchell - PA	West Penn Power Co.	Washington	PA	40.2167	79.9667
Mitchell - WV	Ohio Power Co.	Marshall	WV	39.8297	80.8153
Mohave	Southern California Edison Co.	Clark	NV	35.1667	114.6
Monroe	Detroit Edison Co.	Monroe	MI	41.8911	83.3444
Morgantown	Potomac Electric Power Co.	Charles	MD	38.3611	76.9861
Mountaineer (1301)	Appalachian Power Co.	Mason	WV	38.9794	81.9344
Mt Storm	Virginia Electric & Power Co.	Grant	WV	39.2014	79.2667
Muscatine Plant #1	Muscatine, City of	Muscatine	IA	41.3917	91.0569
Muskogee	Oklahoma Gas & Electric Co.	Muskogee	OK	35.7653	95.2883
Neal North	MidAmerican Energy Co.	Woodbury	IA	42.3167	96.3667
Neal South	MidAmerican Energy Co.	Woodbury	IA	42.3022	96.3622
Nebraska City	Omaha Public Power District	Otoe	NE	40.625	95.7917
New Castle	Pennsylvania Power Co.	Lawrence	PA	40.9383	80.3683
Newton	Central Illinois Pub Serv. Co.	Jasper	IL	38.9364	88.2778
North Omaha	Omaha Public Power District	Douglas	NE	41.33	95.9467
Northeastern	Public Service Co. of Oklahoma	Rogers	OK	36.4222	95.7047
Nucla	Tri-State G & T Assn., Inc.	Montrose	CO	38.2386	108.5072
Oklaunion	West Texas Utilities Co.	Wilbarger	TX	34.0825	99.1753
Paradise	Tennessee Valley Authority	Muhlenberg	KY	37.2608	86.9783
Petersburg	Indianapolis Power & Light Co.	Pike	IN	38.5267	87.2522
Pleasant Prairie	Wisconsin Electric Power Co.	Kenosha	WI	42.5381	87.9033
Port Washington	Wisconsin Electric Power Co.	Ozaukee	WI	43.3908	87.8686
Portland	Metropolitan Edison Co.	Northampton	PA	40.7525	75.3324
Possum Point	Virginia Electric & Power Co.	Prince William	VA	38.5367	77.2806
Potomac River	Potomac Electric Power Co.	Alexandria	VA	38.8078	77.0372
Presque Isle	Wisconsin Electric Power Co.	Marquette	MI	46.5694	87.3933
R Gallagher	PSI Energy, Inc.	Floyd	IN	38.2631	85.8378
R M Schahfer	Northern Indiana Pub. Serv. Co.	Jasper	IN	41.2167	87.0222
Reid Gardner	Nevada Power Co.	Clark	NV	36.6606	114.625
Richard Gorsuch	American Mun. Power-Ohio, Inc.	Washington	OH	39.3672	81.5208
Riverbend	Duke Power Co.	Gaston	NC	35.36	80.9742
Rodemacher	CLECO Corporation	Rapides	LA	31.395	92.7167
Roxboro	Carolina Power & Light Co.	Person	NC	36.4831	79.0711
Sandow	Texas Utilities Electric Co.	Milam	TX	30.5642	97.0639
Scherer	Georgia Power Co.	Monroe	GA	33.0583	83.8072
Shawnee	Tennessee Valley Authority	McCracken	KY	37.1517	88.775
Shawville	GPU Service Corporation	Clearfield	PA	41.0681	78.3661

(continued)

CCW Disposal Sites (Plants) (continued)

Plant Name	Utility Name	County	State	Latitude	Longitude
Sheldon	Nebraska Public Power District	Lancaster	NE	40.5589	96.7842
South Oak Creek	Wisconsin Electric Power Co.	Milwaukee	WI	42.8014	87.8314
Springerville	Tucson Electric Power Co	Apache	AZ	34.3186	109.1636
St Johns River Power	JEA	Duval	FL	30.4308	81.5508
Stanton Energy Ctr.	Orlando Utilities Comm.	Orange	FL	28.4822	81.1678
Stockton Cogen Company	Stockton Cogen Co (operator: Air Products)	San Joaquin	CA	37.9778	121.2667
Syl Laskin	Minnesota Power, Inc.	St Louis	MN	47.53	92.1617
Tecumseh EC	KPL Western Resources Co.	Shawnee	KS	39.0528	95.5683
Texas-New Mexico	Texas-New Mexico Power Company/Sempra Energy	Robertson	TX	31.0928	96.6933
Titus	Metropolitan Edison Co.	Berks	PA	40.3047	75.9072
Trimble County	Louisville Gas & Electric Co.	Trimble	KY	38.5678	85.4139
Tyrone	Kentucky Utilities Co.	Woodford	KY	38.0213	84.7456
Valley	Wisconsin Electric Power Co.	Milwaukee	WI	43.0303	87.925
Vermilion	Illinois Power Co.	Vermilion	IL	40.1781	87.7481
Victor J Daniel Jr.	Mississippi Power Co.	Jackson	MS	30.5322	88.5569
W A Parish	Houston Lighting & Power Co.	Fort Bend	TX	29.4833	95.6331
W H Weatherspoon	Carolina Power & Light Co.	Robeson	NC	34.5889	78.975
W S Lee	Duke Power Co.	Anderson	SC	34.6022	82.435
Wabash River	PSI Energy, Inc.	Vigo	IN	39.5278	87.4222
Walter C Beckjord	Cincinnati Gas & Electric Co.	Clermont	OH	38.9917	84.2972
Wansley	Georgia Power Co.	Heard	GA	33.4167	85.0333
Warrick	Southern Indiana Gas & Elec. Co.	Warrick	IN	37.915	87.3319
Waukegan	Commonwealth Edison Co.	Lake	IL	42.3833	87.8083
Weston	Wisconsin Public Service Corp.	Marathon	WI	44.8617	89.655
Widows Creek	Tennessee Valley Authority	Jackson	AL	34.8825	85.7547
Will County	Commonwealth Edison Co.	Will	IL	38.8639	90.1347
Wyodak	PacifiCorp	Campbell	WY	44.2833	105.4
Yates	Georgia Power Co.	Coweta	GA	33.4631	84.955

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Attachment B-2: CCW WMU Data

Plant	Facility ID	WMU Type	Area (acres)	Capacity (cubic yards)	Waste Type	Original Liner	Liner Type
A B Brown	42	LF	176	10360000	Ash	compacted clay	clay
A/C Power - Ace Operations	3000	LF	18	1030815	FBC	none/natural soils	no liner
Allen	293	SI	85	1500000	Ash	none/natural soils	no liner
Alma	7	LF	85	2000000	Ash and Coal Waste	composite clay/membrane	composite
Antelope Valley	57	LF	27	3500000	Ash	none/natural soils	no liner
Arkwright	198	LF	54	415907	Ash and Coal Waste	none/natural soils	no liner
Asheville	159	SI	140	3200000	Ash	none/natural soils	no liner
Baldwin	2	SI	107	4000000	Ash and Coal Waste	none/natural soils	no liner
Barry	301	SI	63	1900000	Ash and Coal Waste	none/natural soils	no liner
Bay Front	81	LF	10	350000	Ash	none/natural soils	no liner
Bay Shore	32	LF	85		Ash	none/natural soils	no liner
Belews Creek	167	SI	512	2200000	Ash and Coal Waste	none/natural soils	no liner
Belews Creek	168	LF	315	14000000	Ash	compacted ash	no liner
Ben French	14	LF	4.61		Ash	compacted clay	clay
Big Cajun 2	186	SI	241	4990003	Ash	compacted clay	clay
Big Sandy	138	SI	115	12052100	Ash and Coal Waste	none/natural soils	no liner
Big Stone	15	LF	3.4	80000	Ash	compacted clay	clay
Big Stone	41	LF	106	8000000	Ash	none/natural soils	no liner
Black Dog Steam Plant	2700	LF	96	8936296	FBC	compacted clay	clay
Blue Valley	176	SI	23.1	372000	Ash and Coal Waste	compacted clay	clay
Bowen	143	LF	25.24	491400	Ash	compacted ash	no liner
Bowen	144	LF	25.77	406971	Ash	compacted ash	no liner
Brandon Shores	339	LF	246	5600000	Ash and Coal Waste	none/natural soils	no liner

(continued)

CCW WMU Data (continued)

Plant	Facility ID	WMU Type	Area (acres)	Capacity (cubic yards)	Waste Type	Original Liner	Liner Type
Buck	235	SI	90	4840000	Ash and Coal Waste	none/natural soils	no liner
Bull Run	296	SI	41	650000	Ash and Coal Waste	none/natural soils	no liner
C D McIntosh Jr.	223	LF	26		Ash and Coal Waste	compacted ash	no liner
C P Crane	338	LF	35	800000	Ash	none/natural soils	no liner
Cape Fear	161	SI	60	2300000	Ash	none/natural soils	no liner
Carbon	263	lf	11.7739066		Ash and Coal Waste	none/natural soils	no liner
Cardinal	126	SI	123	8437500	Ash	none/natural soils	no liner
Cayuga	325	SI	280	25000000	Ash and Coal Waste	none/natural soils	no liner
Chalk Point	292	LF	596	4634000	Ash and Coal Waste	none/natural soils	no liner
Cholla	107	SI	171	2600000	Ash	none/natural soils	no liner
Cliffside	163	SI	82	2200000	Ash	compacted clay	clay
Clover	139	LF	22	1000000	Ash	geosynthetic membrane	composite
Coal Creek	29	LF	70	4700000	Ash	compacted clay	clay
Coal Creek	30	LF	220	23000000	Ash	composite clay/membrane	composite
Coleto Creek	190	si	314.6135409		Ash and Coal Waste	compacted clay	clay
Colstrip	89	LF	9		Ash	none/natural soils	no liner
Conemaugh	101	LF	434	82000000	Ash	geosynthetic membrane	composite
Conesville	250	LF	300	10000000	Ash	compacted clay	clay
Conesville	251	LF	100	2500000	Ash and Coal Waste	none/natural soils	no liner
Council Bluffs	94	SI	200		Ash	none/natural soils	no liner
Crawford	272	SI	24.5	642000	Ash and Coal Waste	compacted clay	clay
Crist	157	LF	12		Ash and Coal Waste	none/natural soils	no liner
Cross	264	LF	320		Ash	compacted ash	no liner
Cross	265	LF	30		Ash and Coal Waste	none/natural soils	no liner
Cross	266	LF	30		Ash and Coal Waste	none/natural soils	no liner
Cross	267	LF	230		Ash and Coal Waste	none/natural soils	no liner
Cross	268	LF	60		Ash and Coal Waste	compacted clay	clay

(continued)

CCW WMU Data (continued)

Plant	Facility ID	WMU Type	Area (acres)	Capacity (cubic yards)	Waste Type	Original Liner	Liner Type
Cumberland	294	SI	75	1750000	Ash and Coal Waste	none/natural soils	no liner
Cumberland	303	SI	295	9500000	Ash	none/natural soils	no liner
Dale	151	SI	115	7408274	Ash and Coal Waste	none/natural soils	no liner
Dallman	178	LF	22	1800000	Ash	compacted clay	clay
Dallman	179	SI	417	3800000	Ash	none/natural soils	no liner
Dan E Karn	6	LF	40	1650000	Ash and Coal Waste	geosynthetic membrane	composite
Dan River	234	SI	72	2097000	Ash and Coal Waste	none/natural soils	no liner
Danskammer	24	LF	14	517265	Ash and Coal Waste	geosynthetic membrane	composite
Dave Johnston	13	LF	45	296100	Ash	compacted clay	clay
Dickerson	290	LF	206	12600000	Ash	none/natural soils	no liner
Dolet Hills	245	SI	66	850000	Ash and Coal Waste	none/natural soils	no liner
Dolet Hills	246	LF	109	8500000	Ash	compacted clay	clay
Duck Creek	11	LF	21.3	1500000	Ash	compacted clay	clay
Dunkirk	49	LF	12	1126080	Ash	compacted clay	clay
E D Edwards	276	SI	145	11000000	Ash and Coal Waste	none/natural soils	no liner
E W Brown	313	SI	33	1000000	Ash	none/natural soils	no liner
E W Brown	314	SI	84	2710000	Ash	none/natural soils	no liner
Eckert Station	113	LF	174	6460000	Ash	none/natural soils	no liner
Eckert Station	114	SI	151	7200000	Ash	none/natural soils	no liner
Edgewater	289	LF	25	1655700	Ash and Coal Waste	none/natural soils	no liner
Elmer W Stout	130	SI	10	3420000	Ash	geosynthetic membrane	composite
F B Culley	183	SI	82	2600000	Ash and Coal Waste	none/natural soils	no liner
Fayette Power Prj.	195	SI	190	4351644	Ash	compacted clay	clay
Fayette Power Prj.	196	LF	23	890560	Ash	geosynthetic membrane	composite
Flint Creek	191	LF	40	1508250	Ash and Coal Waste	none/natural soils	no liner
Flint Creek	192	si	35.73857178		Ash and Coal Waste	none/natural soils	no liner
Fort Martin	213	LF	17	1900000	Ash	none/natural soils	no liner

(continued)

CCW WMU Data (continued)

Plant	Facility ID	WMU Type	Area (acres)	Capacity (cubic yards)	Waste Type	Original Liner	Liner Type
Fort Martin	214	LF	61	1400000	Ash	double	composite
Fort Martin	215	LF	121	3700000	Ash and Coal Waste	composite clay/membrane	composite
Frank E Ratts	182	SI	39	1250000	Ash and Coal Waste	none/natural soils	no liner
G G Allen	237	SI	210	6545000	Ash and Coal Waste	none/natural soils	no liner
Gadsden	283	SI	60	484000	Ash and Coal Waste	compacted clay	clay
Gallatin	304	SI	341	4300000	Ash and Coal Waste	none/natural soils	no liner
Gen J M Gavin	135	LF	255	50000000	Ash	composite clay/membrane	composite
Gen J M Gavin	136	SI	300	30000000	Ash and Coal Waste	none/natural soils	no liner
Gen J M Gavin	137	LF	99	12000000	Ash	compacted clay	clay
Genoa	244	LF	100		Ash and Coal Waste	none/natural soils	no liner
Gibson	327	SI	875	55000000	Ash and Coal Waste	none/natural soils	no liner
Gibson	329	LF	85	20000000	Ash	compacted clay	clay
Gorgas	280	SI	250		Ash and Coal Waste	compacted clay	clay
Gorgas	281	SI	283	24100000	Ash and Coal Waste	compacted clay	clay
Gorgas	282	SI	1500	15000000	Ash and Coal Waste	compacted clay	clay
Green River	147	SI	36	2331219	Ash and Coal Waste	none/natural soils	no liner
Greene County	279	SI	480	5000000	Ash	compacted clay	clay
H B Robinson	169	SI	30		Ash and Coal Waste	none/natural soils	no liner
Hammond	203	SI	56	576256	Ash and Coal Waste	none/natural soils	no liner
Harllee Branch	204	SI	324	7898277	Ash and Coal Waste	none/natural soils	no liner
Harllee Branch	205	SI	203	7634000	Ash and Coal Waste	none/natural soils	no liner
Harrison	211	LF	79	18000000	Ash and Coal Waste	composite clay/membrane	composite
Harrison	330	SI	300	28000000	Ash	none/natural soils	no liner
Hatfield's Ferry	112	LF	20	790000	Ash and Coal Waste	compacted ash	no liner
Hennepin	274	SI	150	3460600	Ash and Coal Waste	none/natural soils	no liner
Heskett	87	LF	58	1550000	FBC	compacted clay	clay
Holcomb	65	LF	8		Ash	compacted ash	no liner

(continued)

CCW WMU Data (continued)

Plant	Facility ID	WMU Type	Area (acres)	Capacity (cubic yards)	Waste Type	Original Liner	Liner Type
Homer City	118	LF	247	29636550	Ash and Coal Waste	geosynthetic membrane	composite
Hoot Lake	40	LF	72	800000	Ash and Coal Waste	none/natural soils	no liner
Hugo	193	LF	40	4000000	Ash	compacted ash	no liner
Hugo	194	si	151.0232271		Ash and Coal Waste	compacted clay	clay
Hunter	256	LF	280	12000000	Ash	none/natural soils	no liner
Huntington	255	LF	70	11400000	Ash	none/natural soils	no liner
Intermountain	224	SI	105	4840000	Ash and Coal Waste	geosynthetic membrane	composite
Intermountain	225	LF	339	17800000	Ash	compacted ash	no liner
Intermountain	226	SI	180	5200000	Ash	geosynthetic membrane	composite
J H Campbell	115	SI	267	6900000	Ash and Coal Waste	none/natural soils	no liner
J M Stuart	125	SI	88	8357000	Ash	none/natural soils	no liner
J R Whiting	129	SI	6	140000	Ash	none/natural soils	no liner
Jack McDonough	202	SI	73	1531893	Ash and Coal Waste	none/natural soils	no liner
Jack Watson	220	SI	100		Ash	none/natural soils	no liner
James H Miller Jr.	300	SI	200	5500000	Ash	compacted clay	clay
Jim Bridger	257	LF	120	7940941	Ash	none/natural soils	no liner
Jim Bridger	258	LF	241	24000000	Ash and Coal Waste	none/natural soils	no liner
Jim Bridger	259	SI	140	3400000	Ash and Coal Waste	none/natural soils	no liner
Jim Bridger	262	SI	125	6500000	Ash and Coal Waste	none/natural soils	no liner
John E Amos	120	SI	100	13000000	Ash	none/natural soils	no liner
John E Amos	121	LF	200	14000000	Ash and Coal Waste	compacted clay	clay
John E Amos	122	SI	10	3078000	Ash	none/natural soils	no liner
John Sevier	297	SI	57	1600000	Ash and Coal Waste	none/natural soils	no liner
John Sevier	298	LF	51	4800000	Ash	compacted clay	clay
John Sevier	309	SI	105	7000000	Ash and Coal Waste	none/natural soils	no liner
Johnsonville	306	SI	91	2900000	Ash and Coal Waste	none/natural soils	no liner
Joliet 29	275	SI	63.1	1012000	Ash and Coal Waste	none/natural soils	no liner

(continued)

CCW WMU Data (continued)

Plant	Facility ID	WMU Type	Area (acres)	Capacity (cubic yards)	Waste Type	Original Liner	Liner Type
Keystone	106	LF	155	22663120	Ash and Coal Waste	none/natural soils	no liner
Killen Station	254	SI		99935	Ash and Coal Waste	compacted clay	clay
Kingston	311	SI	41	11000000	Ash and Coal Waste	none/natural soils	no liner
Kingston	312	SI	275	8900000	Ash and Coal Waste	none/natural soils	no liner
Kraft	206	si	59.87027428		Ash and Coal Waste	none/natural soils	no liner
L V Sutton	231	SI	162	7696000	Ash and Coal Waste	none/natural soils	no liner
Lansing	64	SI	15		Ash	compacted clay	clay
Laramie R Station	260	SI	10.7	464156	Ash and Coal Waste	compacted clay	clay
Laramie R Station	261	SI	38	939605	Ash	geosynthetic membrane	composite
Lawrence EC	109	LF	825	34300000	Ash	compacted clay	clay
Lawrence EC	110	LF	22	1360000	Ash	compacted clay	clay
Lawrence EC	111	LF	30	1000000	Ash	compacted clay	clay
Lee	240	SI	35	1936000	Ash and Coal Waste	none/natural soils	no liner
Leland Olds	103	LF	37	1800000	Ash	compacted clay	clay
Leland Olds	104	LF	20	458000	Ash and Coal Waste	none/natural soils	no liner
Lon Wright	98	LF		170000	Ash	none/natural soils	no liner
Louisa	63	SI	30	500000	Ash	compacted clay	clay
Marion	52	LF	105	2200000	Ash	none/natural soils	no liner
Marion	53	LF	38	1000000	Ash	compacted clay	clay
Marshall	232	LF	110	7826000	Ash	none/natural soils	no liner
Marshall	233	SI	340	19689000	Ash and Coal Waste	none/natural soils	no liner
Martin Lake	152	LF	290	30000000	Ash	compacted clay	clay
Mayo	171	SI	30	185000	Ash	none/natural soils	no liner
Mayo	172	SI	65	2400000	Ash	none/natural soils	no liner
Meramec	175	SI	61.1	591200	Ash and Coal Waste	none/natural soils	no liner
Merom	184	LF	65	8500000	Ash	none/natural soils	no liner
Miami Fort	39	LF	80	4000000	Ash	compacted clay	clay

(continued)

CCW WMU Data (continued)

Plant	Facility ID	WMU Type	Area (acres)	Capacity (cubic yards)	Waste Type	Original Liner	Liner Type
Milton R Young	100	LF	80	6500000	Ash	compacted clay	clay
Mitchell - PA	208	LF	70	5600000	Ash	none/natural soils	no liner
Mitchell - WV	131	SI		12030000	Ash and Coal Waste	none/natural soils	no liner
Mohave	72	LF	250	21500000	Ash	none/natural soils	no liner
Monroe	26	LF	400	20000000	Ash and Coal Waste	none/natural soils	no liner
Monroe	27	SI	400	15000000	Ash	none/natural soils	no liner
Morgantown	291	LF	212	7700000	Ash and Coal Waste	none/natural soils	no liner
Mountaineer (1301)	212	LF	60	9700000	Ash	composite clay/membrane	composite
Mt Storm	73	LF	125	18920000	Ash	composite clay/membrane	composite
Mt Storm	134	LF	900	8800000	Ash and Coal Waste	compacted clay	clay
Muscatine Plant #1	70	LF	36	2000000	Ash	compacted clay	clay
Muskogee	51	LF	36	1247112	Ash	compacted clay	clay
Neal North	92	SI	150		Ash and Coal Waste	none/natural soils	no liner
Neal North	93	LF	200		Ash	none/natural soils	no liner
Neal South	284	LF	150		Ash	none/natural soils	no liner
Nebraska City	20	LF	17	600000	Ash and Coal Waste	compacted clay	clay
New Castle	66	LF	27	1100000	Ash and Coal Waste	geosynthetic membrane	composite
Newton	180	LF	309		Ash	none/natural soils	no liner
North Omaha	17	LF	13	105000	Ash and Coal Waste	compacted clay	clay
Northeastern	142	LF	69	3185190	Ash	none/natural soils	no liner
Nucla	96	LF	41.2	1500000	FBC	none/natural soils	no liner
Oklaunion	228	SI	11	408940	Ash and Coal Waste	none/natural soils	no liner
Oklaunion	229	SI	19.4	718060	Ash	none/natural soils	no liner
Oklaunion	230	SI	290.8	6056820	Ash	none/natural soils	no liner
Paradise	146	SI	85	7582510	Ash	composite clay/membrane	composite
Paradise	316	SI	200	5000000	Ash	none/natural soils	no liner
Petersburg	155	LF	250	19750000	Ash	compacted clay	clay

(continued)

CCW WMU Data (continued)

Plant	Facility ID	WMU Type	Area (acres)	Capacity (cubic yards)	Waste Type	Original Liner	Liner Type
Petersburg	156	si	156.6901408		Ash	none/natural soils	no liner
Pleasant Prairie	243	LF	26	6500000	Ash and Coal Waste	geosynthetic membrane	composite
Port Washington	242	LF	300	1900000	Ash and Coal Waste	compacted clay	clay
Portland	67	LF	15	2200000	Ash and Coal Waste	none/natural soils	no liner
Possum Point	77	SI	56		Ash and Coal Waste	none/natural soils	no liner
Potomac River	140	LF	33	802000	Ash	geosynthetic membrane	composite
Presque Isle	116	LF	292	14200000	Ash	none/natural soils	no liner
R Gallagher	326	SI	170	20000000	Ash and Coal Waste	compacted clay	clay
R M Schahfer	84	SI	80	1030000	Ash and Coal Waste	none/natural soils	no liner
R M Schahfer	85	LF	200	17200000	Ash	none/natural soils	no liner
Reid Gardner	95	LF	112.5	4520000	Ash	none/natural soils	no liner
Richard Gorsuch	36	LF		3003600	Ash	compacted clay	clay
Riverbend	165	SI	143	3200000	Ash	none/natural soils	no liner
Rodemacher	247	SI	36	1200000	Ash	compacted clay	clay
Rodemacher	248	SI	109	2500000	Ash	compacted clay	clay
Roxboro	239	LF	55	4165000	Ash	none/natural soils	no liner
Sandow	153	LF	125	1300000	Ash	compacted clay	clay
Sandow	187	LF	48	903467	Ash and Coal Waste	none/natural soils	no liner
Sandow	188	SI	45	1351973	Ash and Coal Waste	none/natural soils	no liner
Scherer	199	SI	490	22262030	Ash and Coal Waste	none/natural soils	no liner
Shawnee	317	SI	180	5810000	Ash and Coal Waste	none/natural soils	no liner
Shawnee	318	LF	96	6100000	FBC	none/natural soils	no liner
Shawville	209	LF	68	8000000	Ash	none/natural soils	no liner
Sheldon	23	LF	9	375000	Ash	compacted clay	clay
South Oak Creek	3	LF	45	4050000	Ash and Coal Waste	compacted clay	clay
South Oak Creek	4	LF	130	4600000	Ash	none/natural soils	no liner
Springerville	154	LF	57	6400000	Ash	none/natural soils	no liner

(continued)

CCW WMU Data (continued)

Plant	Facility ID	WMU Type	Area (acres)	Capacity (cubic yards)	Waste Type	Original Liner	Liner Type
St Johns River Power	158	lf	128.624166		Ash and Coal Waste	compacted clay	clay
Stanton Energy Ctr.	117	LF	312		Ash	none/natural soils	no liner
Stockton Cogen Company	2000	LF	4	533333	FBC	composite clay/membrane	composite
Syl Laskin	68	SI	75	726000	Ash and Coal Waste	none/natural soils	no liner
Tecumseh EC	177	LF	540		Ash	compacted clay	clay
Texas-New Mexico	3900	LF	61	6142473	FBC	compacted clay	clay
Titus	207	LF	39	3000000	Ash and Coal Waste	composite clay/membrane	composite
Trimble County	69	SI	115	6856667	Ash	compacted clay	clay
Tyrone	148	SI	5.5	351699	Ash	none/natural soils	no liner
Tyrone	149	SI	5	327500	Ash and Coal Waste	none/natural soils	no liner
Tyrone	150	SI	7.75	500123	Ash and Coal Waste	none/natural soils	no liner
Valley	8	LF	16.4	534000	Ash and Coal Waste	compacted clay	clay
Vermilion	55	SI	43	8100000	Ash and Coal Waste	none/natural soils	no liner
Victor J Daniel Jr	287	lf	49.20163084		Ash	compacted clay	clay
Victor J Daniel Jr	288	si	20.03879417		Ash and Coal Waste	composite clay/membrane	composite
W A Parish	189	lf	28.68322214		Ash	compacted clay	clay
W H Weatherspoon	236	SI	26	1200000	Ash and Coal Waste	none/natural soils	no liner
W S Lee	238	SI	41	1634000	Ash and Coal Waste	none/natural soils	no liner
Wabash River	324	SI	120	14000000	Ash and Coal Waste	none/natural soils	no liner
Walter C Beckjord	123	LF	14	1000000	Ash	compacted ash	no liner
Walter C Beckjord	124	SI		2000000	Ash	none/natural soils	no liner
Wansley	200	SI	330	18712850	Ash and Coal Waste	none/natural soils	no liner
Wansley	201	SI	43		Ash	none/natural soils	no liner
Warrick	181	SI	140	4500000	Ash and Coal Waste	compacted clay	clay
Waukegan	54	LF	60	4000000	Ash and Coal Waste	compacted clay	clay
Weston	241	LF	18	600000	Ash	none/natural soils	no liner
Widows Creek	320	SI	110	3500000	Ash and Coal Waste	none/natural soils	no liner

(continued)

CCW WMU Data (continued)

Plant	Facility ID	WMU Type	Area (acres)	Capacity (cubic yards)	Waste Type	Original Liner	Liner Type
Widows Creek	321	SI	222	12400000	Ash	compacted clay	clay
Will County	277	SI	60	599256	Ash and Coal Waste	compacted clay	clay
Wyodak	71	LF	68	3500000	Ash	geosynthetic membrane	composite
Yates	197	SI	4.7	115000	Ash	composite clay/membrane	composite

Appendix C. Site Data

The site characteristics used in this analysis were based on site-specific, regional, and national data sources to provide the environmental parameters necessary for modeling the fate and transport of coal combustion waste (CCW) constituents released in landfill or surface impoundment leachate. Site-specific data were collected for the area in the immediate vicinity of the waste management unit (WMU), and included the geographic relationship among important features such as the WMU boundary, residential well location, and streams and lakes. These data were collected at each of the 181 coal-fired power plants selected for the analysis. These 181 locations across the continental United States were intended to represent the geographic distribution of onsite WMUs used for disposal of CCW and were used to capture national variability in meteorology, soils, climate, aquifers, and surface waterbodies at the disposal sites.

C.1 Data Collection Methodology

The CCW risk assessment employed site-specific, regional, and national data. Site-specific data were collected around CCW plant locations from the Energy Information Administration (EIA) database to obtain data for each facility that were representative of the environment immediately surrounding the plant. When site-specific data were not available, regional or national scale data sources were used. Where appropriate, distributions were used in the Monte Carlo analysis to capture site-to-site, within-site, and national variability in the parameters collected.

Data were collected around each CCW site using a geographic information system (GIS) that allowed (1) site-specific data to be assembled from the area immediately surrounding the facility and (2) the site to be assigned to a region to collect regional data. To account for locational uncertainty for the CCW WMUs[1], a 5-km radius was used to define the data collection area for aquifer type and soil data. If multiple soil or aquifer types occurred within this radius, multiple types were sent to the model, weighted by the fraction of the collection area that they occupied. Surface waterbody type and stream flows also were collected for each site by identifying the nearest stream segment.

Climate and water quality data were collected by assigning each site to a Hydrologic Evaluation of Landfill Performance (HELP) model climate station and a U.S. Geological Survey (USGS) hydrologic region. The EPA STOrage and RETrieval (STORET) database was used as the source for water quality data, with parameters selected from distributions queried from this database for each region.

Because the EIA locations were not exact for the WMUs being modeled, a national distribution of stream distances was developed by manually measuring the distance between the

[1] The EIA latitudes and longitudes usually represent a facility centroid or front-gate location for each power plant. Because these facilities are often large, the WMUs are frequently located some distance from the plant itself and not at the EIA location.

WMU and the waterbody at a random sample of the CCW sites. Similarly, a national distribution was used to represent the distance of the nearest residential wells from the CCW WMUs being modeled.

C.2 Receptor Location (National Data)

The residential scenario for the CCW groundwater pathway analysis calculates exposure through use of well water as drinking water. During the Monte Carlo analysis, the receptor well was placed at a distance of up to 1 mile from the edge of the WMU, by sampling a nationwide distribution of nearest downgradient residential well distances taken from a survey of municipal solid waste landfills (U.S. EPA, 1988).

EPA believes that this MSW well-distance distribution (presented in **Table C-1**) is protective for onsite CCW landfills and surface impoundments at coal-fired utility power plants, but recognizes that this is an uncertainty in this analysis. Because CCW plants tend to be in more isolated areas than MSW landfills and because CCW WMUs tend to be larger than municipal landfills, EPA believes that the MSW well distance distribution is a protective representation of actual well distances at CCW disposal sites. As discussed in **Section 3.4.3**, the groundwater model used in the CCW risk assessment placed limits on the lateral direction from the plume centerline (i.e., angle off plume centerline) and depth below the water table to ensure that the well remained within the plume and at a depth appropriate for surficial aquifers across the United States. These limits were consistent with other recent national risk assessments conducted by EPA OSW and provided a protective approach to siting wells for this analysis.

Table C-1. Distribution of Receptor Well Distance

Percentile	x-distance (m)
Minimum	0.6
10	104
20	183
30	305
40	366
50 (Median)	427
60	610
70	805
80	914
90	1,220
Maximum	1,610

Source: U.S. EPA (1988).

C.2.1 Recreational Fisher and Ecological Risk Scenario (Distance to Waterbody)

The recreational fisher scenario was used to estimate risks to recreational fishers and their children who live in the vicinity of the CCW landfills and surface impoundments and catch and consume fish from a waterbody located adjacent to the buffer. The waterbody was assumed to be a stream or lake located downwind of the WMU, beginning where the buffer area ends (see Figure 2-4), and was also used as the reasonable worst case aquatic system for the ecological risk

assessment. Waterbody characteristics were determined based on site-specific, regional, or national data (as described in **Section C.6**), except for stream length, which was determined by the width of the plume as it intersects the waterbody.

The downgradient distance to the surface water body was determined from a national distribution developed by measuring this distance at 59 CCW landfill and surface impoundment sites randomly selected from the 204 WMUs modeled in this risk assessment. **Table C-2** presents this distribution. **Figure C-1** provides a map and aerial photo of one of the facilities used to develop this distribution. The development of this distribution is described in **Section C.6.4**.

Table C-2. Distribution of Surface Water Distances

Percentile	Distance (m)
Minimum	10
0.03	10
0.05	20
0.07	20
0.09	20
0.10	20
0.13	20
0.15	30
0.20	40
0.25	50
0.30	50
0.35	60
0.40	70
0.45	100
0.50 (Median)	120
0.55	130
0.60	150
0.65	250
0.70	400
0.75	440
0.80	500
0.85	700
0.87	775
0.90	800
0.91	1,000
0.93	1,500
0.95	2,125
0.97	2,750
Maximum	3,000

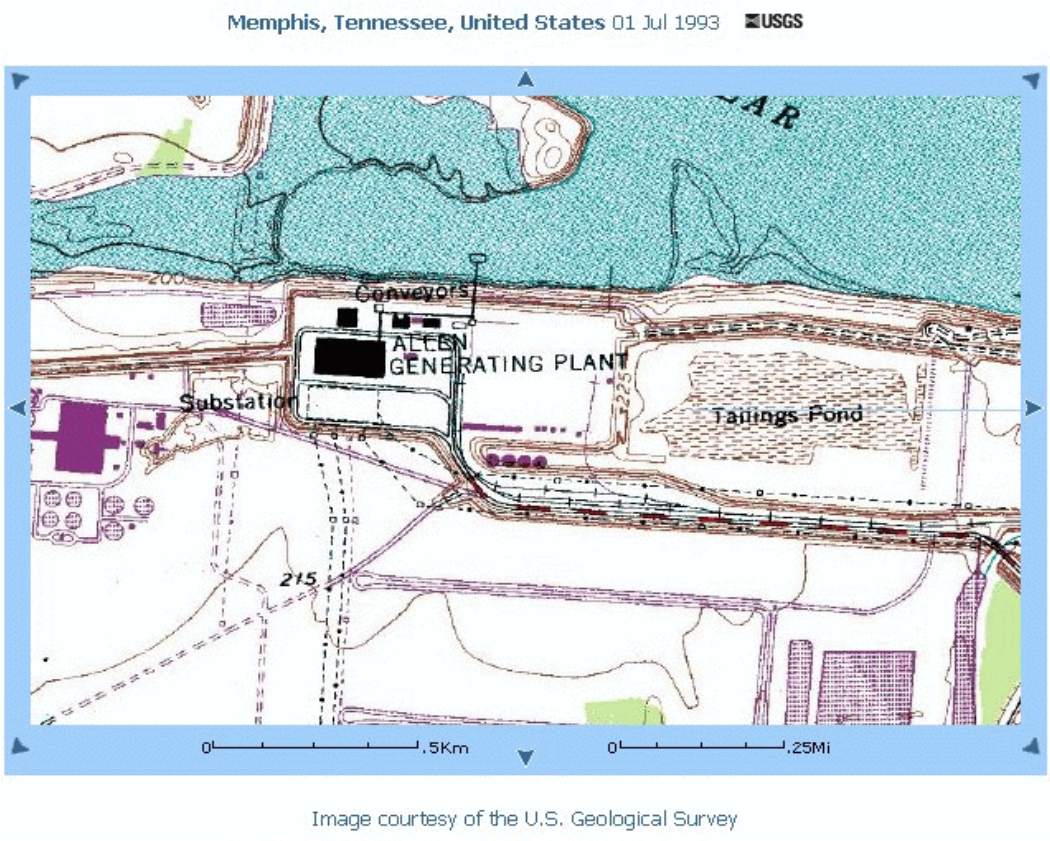

Figure C-1. Example CCW site used to develop waterbody distance distribution.

C.3 Soil Data

The groundwater model used in the CCW risk assessment—EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP)—requires soil properties for the entire soil column to model leachate transport through the vadose zone to groundwater. As with aquifer type, soil data were collected within a 5-km radius of each CCW plant. A GIS was used to identify soil map units within a 20-mile radius around each meteorological station. Database programs were then used to assemble and process soil texture, pH, and soil organic matter data for these map units from the State Soil Geographic (STATSGO) database. Both pH and soil organic matter were processed and indexed by the soil textures present within the 5-km radius. Soil properties are listed by texture for each of the 181 CCW plants in **Attachment C-1**.

C.3.1 Data Sources

The primary data source for soil properties was the STATSGO database. STATSGO is a repository of nationwide soil properties compiled primarily by the U.S. Department of Agriculture (USDA) from county soil survey data (USDA, 1994). STATSGO includes a 1:250,000-scale GIS coverage that delineates soil map units and an associated database containing soil data for each STATSGO map unit. (Map units are areas used to spatially represent soils in the database.)

In addition, two compilations of STATSGO data, each keyed to the STATSGO map unit GIS coverage, were used in the analysis as a convenient source of average soil properties:

- **USSOILS.** The USSOILS data set (Schwarz and Alexander, 1995) averages STATSGO data over the entire soil column for each map unit.
- **CONUS.** The Conterminous United States Multi-Layer Soil Characteristics (CONUS) data set (Miller and White, 1998) provides average STATSGO data by map unit and a set of 11 standardized soil layers.

Soil organic matter and pH were derived directly from USSOILS and STATSGO data. A complete set of hydrological soil properties[2] was not available from STATSGO. To ensure consistent and realistic values, EPACMTP relies on established, nationwide relationships between hydrologic properties and soil texture. Peer-reviewed publications by Carsel and Parrish (1988) and Carsel et al. (1988) provide a consistent set of correlated hydrologic properties for each soil texture. Soil texture data for the entire soil column were collected from the CONUS database.

C.3.2 Methodology

The soil data collection methodology began with GIS programs (in Arc Macro Language [AML]). These programs overlaid a 5-km radius around each CCW plant location on the STATSGO map unit coverage to determine the STATSGO map units and their area within the radius. These data were then passed to data processing programs that derive soil properties for

[2] Hydrological soil properties required by EPACMTP include bulk density, saturated water content, saturated hydraulic conductivity, and the van Genuchten soil moisture retention parameters alpha and beta.

each site, either through direct calculations or by applying established relationships in lookup tables.

EPACMTP utilizes three soil textures to represent variability in hydrologic soil properties and (along with climate data) to assign infiltration rates to each site. Because STATSGO soils are classified into the 12 U.S. Soil Conservation Service (SCS) soil textures, the crosswalk shown in **Table C-3** was used to assign the SCS textures to the EPACMTP megatextures and to calculate the percentage of each megatexture within the 5-km data collection radius. These percentages were sampled for each site when preparing the source data file for each site.

Both soil pH and soil organic matter were derived for each EPACMTP soil megatexture at a site. During source data file preparation, when a megatexture was picked for a particular iteration of a site, the corresponding pH and organic matter values were selected as well.

Table C-3. EPACMTP Soil Texture Crosswalk

STATSGO Texture	EPACMTP Megatexture
Sand	Sandy loam
Loamy sand	
Sandy loam	
Silt loam	Silt loam
Silt	
Loam	
Sandy clay loam	
Clay loam	
Silty clay loam	Silty clay loam
Sandy clay	
Silty clay	
Clay	

C.3.3 Results

Attachment C-1 lists the STATSGO soil textures and EPACMTP megatexture assignments and percentages for each CCW disposal site.

C.4 Hydrogeologic Environments (Aquifer Type)

To assign aquifer properties used by EPACMTP, it was necessary to designate hydrogeologic environments (or aquifer types) for each of the locations modeled so that correlated, national aquifer property data could be used in the analysis. EPACMTP uses the Hydrogeologic Database (HGDB) developed by the American Petroleum Institute (API) (Newell et al., 1989; Newell et al., 1990) to specify correlated probability distributions, which were used to populate the following four hydrogeologic parameters during the Monte Carlo analysis:

- Unsaturated zone thickness
- Aquifer thickness

- Hydraulic gradient
- Saturated hydraulic conductivity.

The HGDB provides correlated data on these hydrogeologic parameters and an aquifer classification for approximately 400 hazardous waste sites nationwide, grouped according to 12 hydrogeologic environments described in Newell et al. (1990). The *EPACMTP User's Guide* (U.S. EPA, 1997) provides the empirical distributions of the four hydrogeologic parameters for each of the hydrogeologic environments.

Average aquifer/vadose zone temperature was also required for the groundwater model and was obtained from a digitized map of groundwater temperatures for the continental United States from the *Water Encyclopedia* (van der Leeden et al., 1990).

The hydrogeologic environment approach to assigning EPACMTP aquifer variables relied upon a hydrogeologic framework originally developed for an attempt by EPA to classify and score groundwater environments according to their potential to be polluted by pesticide application. Although this DRASTIC[3] scoring system was not widely applied to determining groundwater vulnerability to pesticide pollution, the hydrogeologic framework established for the effort has proven very useful in categorizing geologic settings in terms of the aquifer characteristics needed for groundwater modeling. The major components of this modeling framework are Groundwater Regions, hydrogeologic settings, and hydrogeologic environments, as described below:

- The fifteen **Groundwater Regions**, defined by Heath (1984), provide a regional framework that groups hydrogeologic features (i.e., nature and extent of dominant aquifers and their relationship to other geologic units) that influence groundwater occurrence and availability.

- **Hydrogeologic settings** were developed within each Heath region by Aller et al. (1987)[4] to create mappable geological units that are at the proper scale to capture differences in aquifer conditions. Note that there may be the same or similar settings across different regions (e.g., the alluvial settings). Within each region, Aller et al. (1987) describe each setting with a written narrative and provide a block diagram to visualize the geology, geomorphology, and hydrogeology.

- **Hydrogeologic environments** were developed by Newell et al. (1990) as the geologic framework for the API's HGDB. To create the 12 environments, Newell et al. rolled up similar hydrologic settings across the Groundwater Regions to group settings with similar aquifer characteristics (hydraulic conductivity, gradient, thickness, and depth-to-water). **Table C-4** shows the crosswalk between hydrologic environment and hydrogeologic setting, organized by Groundwater Region.

[3] The DRASTIC scoring factors are Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone media, and aquifer hydraulic Conductivity.

[4] Aller et al. (1987, p. 14) did not develop settings for Region 15 (Puerto Rico and the Virgin Islands) and reincorporated Region 12 (Alluvial Valleys) into each of the other regions as "river alluvium with overbank deposits" and "river alluvium without overbank deposits."

Because EPACMTP uses the HGDB for national and regional analyses (using a regional site-based approach), it was necessary to assign the CCW sites to a hydrogeologic environment so that the correct HGDB data set would be used for modeling each site. The data sources and methodology used to make these assignments are described below.

C.4.1 Data Sources

Data sources used to make hydrogeologic assignments for the sites included:

- A USGS inventory of state groundwater resources (Heath, 1985)
- GIS coverages from *Digital Data Sets Describing Principal Aquifers, Surficial Geology, and Ground-Water Regions of the Conterminous United States* (Clawges and Price, 1999a-d)
- GIS coverages of principal aquifers from the USGS *Groundwater Atlas* (Miller, 1998)
- STATSGO soil texture data (described in Section C.3.2).

These coverages were used in a GIS overlay process to determine the principal aquifers, surficial geologic units, groundwater region, productive aquifers, and general hydrogeologic settings for a 5-km radius around each CCW facility location. Attributes for each of these items were passed to a database for use in assigning hydrogeologic environments.

C.4.2 Assignment Methodology

For each CCW site, hydrogeologic environments were assigned by a professional geologist as follows:

- Determine Heath Groundwater Region (for the Alluvial Valleys region, determine the region in which the alluvial valley is located)
- Assign hydrogeologic setting using state geological descriptions from Heath (1985); aquifer, soil, and surficial geology information obtained using GIS; and narratives and block diagrams from Aller et al. (1987)
- Using the look-up table from Newell et al. (1990), determine hydrogeologic environment from hydrogeologic setting.

In general, the surficial geology coverage had better resolution than the aquifer coverages and was used to develop setting percentages for the 5-km radius. In most cases, there were two settings per site. In cases where a single setting accounted for over 80 percent of the 5-km area, a single setting was assigned.

Because Newell et al. (1990) define two alluvial environments (6, River alluvium with overbank deposits, and 7, River alluvium without overbank deposits), it was necessary to determine which environment an alluvial site fell into. The survey soil layer information was used to distinguish between these two settings by determining whether there were significant fine-grained overbank deposits in the soil column.

Quality assurance/quality control (QA/QC) measures included independent review of the assignments by other geologists with expertise in assigning settings.

C.4.3 Data Processing

HGDB hydrogeologic environment fractions (i.e., the portion of the region assigned to each of the 12 hydrogeological environments) were defined and used in the CCW risk assessment as follows. If the 5-km radius around a site contained only one HGDB environment, the fraction assigned was 1.0 and all groundwater model runs for that location were associated with that hydrological environment. If more than one HGDB environment was present, each environment was assigned a fraction based on the areal percentages of each setting within the 5-km radius.

These fractions were used to generate the hydrogeologic environment for that location for each iteration of the Monte Carlo groundwater modeling analysis. For example, if two hydrogeologic environments were assigned to a CCW site with a fraction of 0.5, half of the realizations were modeled with the first hydrogeologic environment and half with the second.

Once the hydrogeologic environments were assigned, a preprocessing run of EPACMTP was conducted to construct a set of randomly generated but correlated hydrogeologic parameter values for each occurrence of the hydrogeologic environments in the source data files. Missing values in the HGDB data set were filled using correlations, as described in U.S. EPA (1997).

C.4.4 Results

Attachment C-2 lists the hydrogeologic environment assignments for each CCW disposal site. **Table C-4** summarizes these results, showing the crosswalk between Groundwater Regions, hydrogeologic settings, and hydrogeologic environments used to make the assignments, along with the number of CCW sites for each setting. **Table C-5** totals the number of CCW disposal sites for each hydrogeologic environment sent to EPACMTP.

Table C-4. Groundwater Regions, Hydrogeologic Settings, and Hydrogeologic Environments: CCW Disposal Sites

Hydrogeologic Setting		Hydrogeologic Environment	Number of CCW Sites
Alluvial Basins			
2C	Alluvial Fans	5	1
2E	Playa Lakes	5	1
2Ha	River Alluvium With Overbank Deposits	6	1
Colorado Plateau and Wyoming Basin			
4B	Consolidated Sedimentary Rock	2	7
4C	River Alluvium	7	3
High Plains			
5Gb	River Alluvium Without Overbank Deposits	7	1

(continued)

Groundwater Regions, Hydrogeologic Settings, and Hydrogeologic Environments: CCW Disposal Sites. (continued)

Hydrogeologic Setting		Hydrogeologic Environment	Number of CCW Sites
Nonglaciated Central Region			
6Da	Alternating Sandstone, Limestone, and Shale – Thin Soil	2	22
6Db	Alternating Sandstone, Limestone, and Shale – Deep Regolith	2	6
6E	Solution Limestone	12	9
6Fa	River Alluvium With Overbank Deposits	6	37
6Fb	River Alluvium Without Overbank Deposits	7	4
6H	Triassic Basins	2	4
Glaciated Central Region			
7Aa	Glacial Till Over Bedded Sedimentary Rock	3	12
7Ac	Glacial Till Over Solution Limestone	12	6
7Ba	Outwash	8	1
7Bb	Outwash Over Bedded Sedimentary Rock	2	3
7Bc	Outwash Over Solution Limestone	12	2
7D	Buried Valley	4	11
7Ea	River Alluvium With Overbank Deposits	6	24
7Eb	River Alluvium Without Overbank Deposits	7	6
7F	Glacial Lake Deposits	4	3
7G	Thin Till Over Bedded Sedimentary Rock	3	5
7H	Beaches, Beach Ridges, and Sand Dunes	11	1
Piedmont and Blue Ridge			
8B	Alluvial Mountain Valleys	5	1
8C	Mountain Flanks	2	2
8D	Regolith	1	13
8E	River Alluvium	6	6
Northeast and Superior Uplands			
9E	Outwash	8	3
9F	Moraine	4	1
9Ga	River Alluvium With Overbank Deposits	6	1
Atlantic and Gulf Coastal Plain			
10Aa	Regional Aquifers	4	1
10Ab	Unconsolidated/Semiconsolidated Shallow Surficial Aquifers	10	20
10Ba	River Alluvium With Overbank Deposits	6	7
10Bb	River Alluvium Without Overbank Deposits	7	6
Southeast Coastal Plain			
11A	Solution Limestone and Shallow Surficial Aquifers	12	3
11B	Coastal Deposits	4	1

Table C-5. Hydrogeologic Environments for CCW Disposal Sites

Hydrogeologic Environment		Number of CCW Sites
1	Metamorphic and Igneous	13
2	Bedded Sedimentary Rock	44
3	Till Over Sedimentary Rock	17
4	Sand and Gravel	17
5	Alluvial Basins Valleys and Fans	3
6	River Valleys and Floodplains With Overbank Deposit	76
7	River Valleys and Floodplains Without Overbank Deposits	20
8	Outwash	4
9	Till and Till Over Outwash	0
10	Unconsolidated and Semiconsolidated Shallow Aquifers	20
11	Coastal Beaches	1
12	Solution Limestone	20

C.5 Climate Data

The CCW risk assessment selected EPACMTP meteorological (or climate) stations for each CCW disposal site to collect the climatic data necessary for fate and transport modeling. For each station, the following data were compiled:

- Mean annual windspeed
- Mean annual air temperature
- Mean annual precipitation.

With respect to precipitation, EPACMTP uses the climate station, along with soil texture, to select the HELP-modeled infiltration rates to use in the landfill source model and recharge rates to use in EPACMTP (see **Section 3.2.2**). The surface water model uses mean annual windspeed and average air temperature to estimate volatilization losses from the surface waterbodies modeled in the analysis.

To assign the EPACMTP/HELP climate centers to each CCW site, a GIS was used to determine the three meteorological stations closest to the plant. These assignments were passed to a meteorologist, who reviewed the closest stations against plots of the CCW sites and the climate centers on a downloadable map (http://www.nationalatlas.gov) of annual average precipitation rates for the period from 1961 to 1990 across the contiguous United States. (**Figure C-2**). The meteorologist compared the 5-year average precipitation range for each EPACMTP climate center to precipitation ranges for each plant from the map. In most cases, the precipitation rate for the nearest climate center fell within the site's expected precipitation range, and the nearest climate center was assigned in those cases. In some cases, the precipitation rates from the nearest climate center did not fall within the site's expected range. When this occurred, the second or third closest climate center was examined and matched based on:

- A 5-year precipitation average within or close to the site's predicted precipitation range

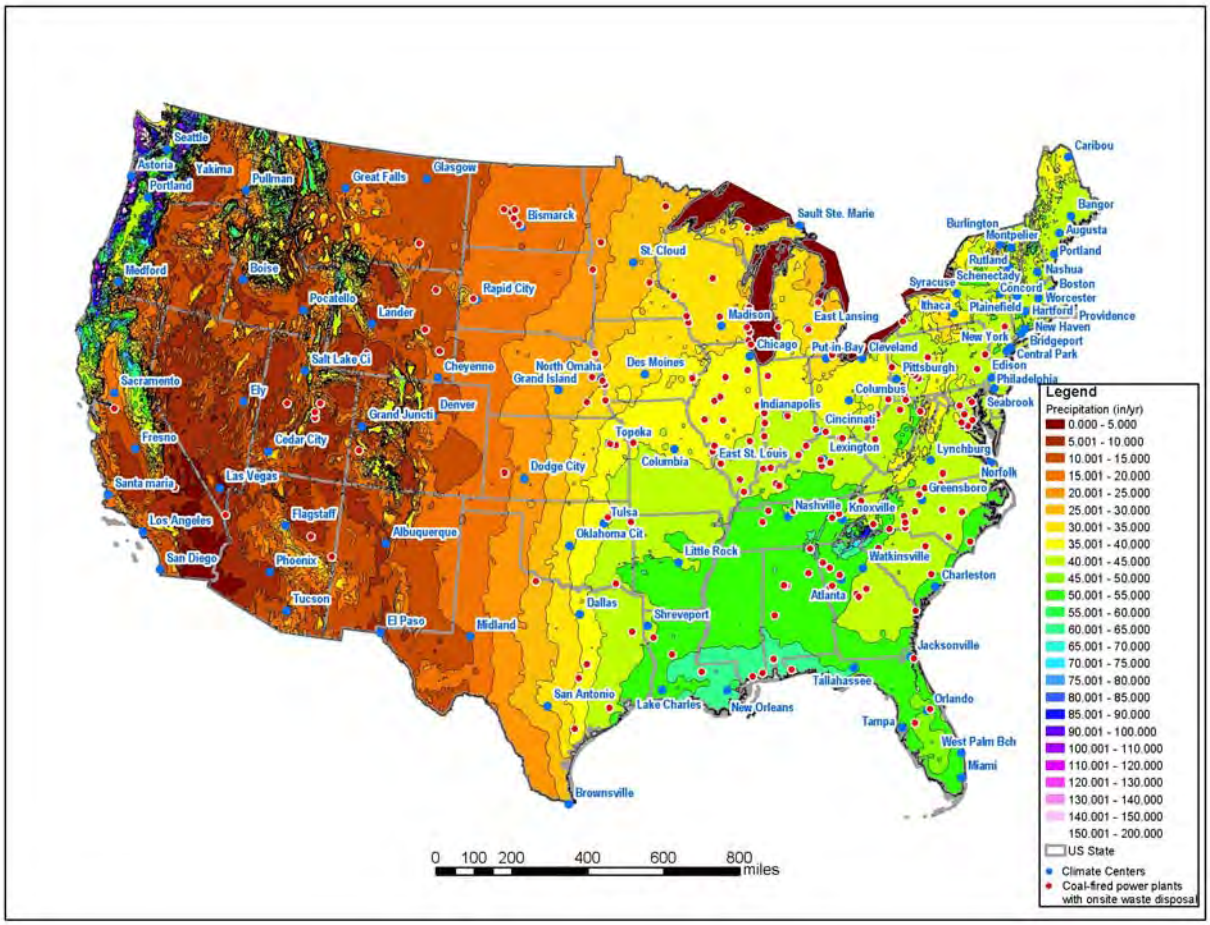

Figure C-2. EPACMTP climate centers, precipitation ranges, and CCW disposal sites.

- Confirmation of a site's average annual rainfall on http://www.weather.com and van der Leeden et al. (1990)
- Geographic similarities between plant and climate center locations
- Best professional judgment.

In a few cases, the three closest climate centers did not reflect the average precipitation rates for a plant's location. In these cases, other nearby stations were examined and the plant was assigned to the closest climate center with similar geography and average precipitation rates. Each assignment was independently checked for accuracy. **Attachment C-3** lists the climate center assigned to each CCW disposal site, along with notes for plants not assigned to the nearest center. **Table C-6** lists all the climate centers used in the CCW risk assessment along with the number of CCW sites assigned to each station.

Table C-6. EPACMTP Climate Centers Assigned to CCW Disposal Sites

Climate Center		State	Number of CCW Sites
4	Grand Junction	CO	2
6	Glasgow	MT	1
7	Bismarck	ND	5
10	Cheyenne	WY	2
11	Lander	WY	1
13	Sacramento	CA	1
16	Ely	NV	1
17	Rapid City	SD	2
18	Cedar City	UT	1
19	Albuquerque	NM	1
20	Las Vegas	NV	3
21	Phoenix	AZ	1
26	Salt Lake City	UT	1
29	Dodge City	KS	1
31	St. Cloud	MN	3
32	East Lansing	MI	3
33	North Omaha	NE	7
34	Tulsa	OK	2
37	Oklahoma City	OK	1
39	Pittsburgh	PA	12
42	Chicago	IL	8
48	Sault Ste. Marie	MI	1
49	Put-in-Bay	OH	3
50	Madison	WI	9
51	Columbus	OH	2
53	Des Moines	IA	2
54	East St. Louis	IL	8
55	Columbia	MO	1
56	Topeka	KS	3
58	San Antonio	TX	4
66	Ithaca	NY	1
69	Lynchburg	VA	2
71	Philadelphia	PA	2
72	Seabrook	NJ	5
73	Indianapolis	IN	12
74	Cincinnati	OH	11
75	Bridgeport	CT	1
76	Orlando	FL	2
77	Greensboro	NC	11

(continued)

EPACMTP Climate Centers Assigned to CCW Disposal Sites. (continued)

Climate Center		State	Number of CCW Sites
78	Jacksonville	FL	1
79	Watkinsville	GA	4
80	Norfolk	VA	2
81	Shreveport	LA	4
85	Knoxville	TN	4
87	Lexington	KY	3
89	Nashville	TN	4
90	Little Rock	AR	1
91	Tallahassee	FL	4
93	Charleston	SC	4
95	Atlanta	GA	9
96	Lake Charles	LA	2

C.6 Surface Water Data

The surface water model used in the CCW risk assessment requires information on surface waterbody type (river or lake), flow conditions, dimensions, and water quality. In addition, the groundwater model requires the distance between the waterbody and the WMU being modeled. Surface waterbody data were collected on a site-based, regional, or national basis depending on the variable and data availability. Collection methods are described below by data source. **Attachment C-4** provides a summary of waterbody assignments, waterbody types, and flow conditions.

C.6.1 Waterbody Type, Stream Flow Conditions, and Dimensions

Waterbody type and flow parameters were obtained by matching the CCW plants to stream segments in the Reach File Version 1.0 (RF1) database (U.S. EPA, 1990). Stream flow estimates for all RF1 flowing reaches were estimated in the early 1980s. Statistics developed for each flowing reach were mean annual flow, low flow (approximately 7Q10),[5] and mean monthly flow. RF1 also contains velocities corresponding to mean annual and low flow, estimated from a compendium of time-of-travel studies. For streams and rivers, the CCW risk assessment used the low flow statistic and the corresponding flow velocity, along with a waterbody type also included in the RF1 database. All RF1 data are indexed by USGS cataloging unit and stream segment (CUSEG).

To assign the CCW plants to the nearest downgradient reach (i.e., the nearest waterbody in the direction of groundwater flow), a GIS was used to identify the closest RF1 stream segment to each CCW plant location. Because of several uncertainties in the nearest reach approach (i.e.,

[5] The 7Q10 is the minimum 7-day average flow expected to occur within a 10-year return period (i.e., at least once in 10 years).

inaccurate WMU location, unknown direction of groundwater flow, and limited lake coverages), the CCW plants also were matched to standard industrial classification (SIC) code 4911 facilities in EPA's Permit Compliance System (PCS) database (http://www.epa.gov/enviro/html/pcs/index.html), to obtain the PCS information (e.g., name, CUSEG) on the receiving waterbody for the plants' National Pollutant Discharge Elimination System (NPDES) discharge point(s). When the two sources matched, the reach was selected for modeling. When they differed, the PCS data were used, because it was judged more likely that the NPDES receiving waterbody would also be receiving loads from the WMU through the groundwater-to-surface-water pathway. CCW plants that could not be matched to the PCS database were simply assigned the nearest RF1 waterbody.

The next step in the assignment process was to review the waterbody names (especially those from PCS) to identify lakes and reservoirs. Finally, visual review, using aerial photos and topographic maps from the Terraserver Web site (http://www.terraserver.com), was used to check all low-flow streams and RF1 reaches whose identity was not clear. **Attachment C-4** provides the RF1 stream assignments, flows, and waterbody types for the CCW disposal sites.

With respect to waterbody type, the RF1 data include several types of waterbodies, including streams and rivers, and types with zero flows such as lakes, Great Lakes, wide rivers, and coastline features. Each of these waterbody types needed to be designated as a river or a lake for the simple waterbody model used in the full-scale CCW risk assessment. Because only the streams and rivers have flow data in RF1 (i.e., are flowing reaches), all other types were assigned to the lake modeling category. Modeling these features as a simple model lake is an uncertainty in the CCW risk assessment **Table C-7** lists the RF1 waterbody types for the waterbodies assigned to the CCW disposal sites, along with the number of CCW plants assigned to each type and the crosswalk to the river (R) or lake (L) waterbody type used in this risk assessment.

Table C-7. RF1 Reach Types Assigned to CCW Disposal Sites

RF1 Code	RF1Name	Description	Reach Model Type[a]	Number of CCW Plants
Flowing Reaches				
M	Artificial Open Water Reach	An artificial reach within any open water, other than a lake or reservoir, to provide connection between input and output reaches of the open water.	R	1
R	Regular Reach	A reach that has upstream and downstream reaches connected to it and that is not classified as another type of reach.	R	106
S	Start Reach	A headwater reach that has no reaches above it and either one or two transport reaches connected to its downstream end.	R	16
T	Terminal Reach	A reach downstream of which there is no other reach (for example, a reach that terminates into an ocean, a land-locked lake, or the ground). This type of reach has either one or two reaches connected to its upstream end.	R	2

(continued)

RF1 Reach Types Assigned to CCW Disposal Sites. (continued)

RF1 Code	RF1Name	Description	Reach Model Type[a]	Number of CCW Plants
Reaches with Zero RF1 Flow				
C	Coastal/Continental Shoreline Segment	A reach that represents a segment of a shoreline of a gulf, sea, or ocean.	L	3
G	Great Lakes Shoreline Segment	A reach that represents a segment of a shoreline of the Great Lakes.	L	12
L	Lake Shoreline Segment	A segment that follows the shoreline of a lake other than one of the Great Lakes.	L	36
W	Wide-River Shoreline Segment	A reach that represents a segment of the left or right bank of a stream.	L	5

[a] R = river; L = lake.

Stream dimensions were calculated from the flow data as follows. First, the length of the modeled stream segment was set to be the width of the groundwater plume as it enters the waterbody. Stream width was then determined from flow (Q) using a liner regression equation derived from empirical data by Kocher and Sartor (1997):

$$Width = 5.1867Q^{0.4559} \quad \text{(C-1)}$$

Water column depth (dwc) was derived from width, velocity (V), and flow using the continuity equation:

$$dwc = \frac{Q}{v \times Width} \quad \text{(C-2)}$$

C.6.2. Lake Flow Conditions and Dimensions

Areas and depths for many of the lakes assigned to the CCW plant sites were not readily available from RF1, Reach File Version 3 (RF3), the National Hydrography Dataset (NHD), or other sources. In addition, many plants were located on very large waterbodies (e.g., the Great Lakes, wide rivers, or coastlines), where applying the simple steady-state, single-compartment model used in this analysis to the entire lake would not be appropriate. For these reasons, a model lake approach was used to represent all lakes and other nonflowing waterbodies assigned to the CCW disposal site.

The model lake chosen was Shipman City Lake in Illinois, a well-characterized 13-acre lake that EPA has chosen as the index reservoir for modeling drinking water exposures to pesticides (Jones et al., 1998). The parameter values shown in **Table C-8** for Shipman City Lake were used to model all lakes in this initial analysis. Given that many of the lakes assigned to CCW plants were much larger than 13 acres, this produced high-end risk results. However, given that many of the plants were located on very large waterbodies, this necessary simplification is an uncertainty in defining the environmental settings for the CCW risk assessment.

Table C-8. Model Lake Used in CCW Risk Assessment

Parameter	Value
Area [a]	13 acres
Water column depth (dwc)[a]	9 feet
Hydraulic residence time (HRT)	Random, triangular distribution: Minimum = 1 month Mean = 6 months Maximum = 24 months
Annual flow mixing volume	= (Area × dwc) / HRT

[a] Source: Shipman City Lake, IL (Jones et al., 1998).

C.6.3 Water Quality Data

Surface water temperature, total suspended solids (TSS), and pH data were collected by USGS hydrologic region from the STORET database. EPA's STORET system is the largest single source of water quality data in the country. The Legacy STORET database contains over 275 million analyses performed on more than 45 million samples collected from 800,000 stations across the United States for the period 1960 through 1998. STORET can be accessed from the Web at http://www.epa.gov/STORET.

STORET water quality data are notoriously "noisy" because they are influenced by hydrology, point sources, nonpoint sources, stream/lake morphology, and varying data quality. The following issues in using STORET data must be considered before using the data:

- Not all of the data have undergone rigorous QA/QC.
- STORET site locations can be biased, especially to known "problem" waters.
- The sample times are often at critical periods, such as summer low flows.

Statistical analysis techniques were employed taking into account the above issues (including coordination with gage statistical analysis and Reach Files, the use of median values to avoid bias in central tendency estimates, and specification of a minimum number of measurements to estimate median values). As a result of these techniques, which can be thought of as extracting the underlying "signal" of water quality from the inherent "noise" of water quality data, the above issues were manageable.

Surface water temperature data were collected as median values for each hydrologic region. These data are shown in **Table C-9** along with the number of the modeled CCW plants in each region.

Table C-9. Regional Surface Water Temperatures: CCW Disposal Sites

Hydrologic Region	Surface Water Temperature (°C)	Number of CCW Plants
2	16	12
3	21	37
4	14	14
5	17	43
6	18	6
7	15	20
8	20	2
9	10	1
10	13	20
11	17	8
12	21	6
14	9	5
15	17	4
16	9	1
18	15	2

Data source: Legacy STORET database.

Total suspended solids data were collected separately for streams/rivers and lakes because lakes tend to have lower TSS levels. Annual median values were used to develop statistics. For rivers, the minimum, maximum, and geometric mean values were used to define log triangular distributions for each hydrologic region (**Table C-10**); these distributions were then sampled during the preparation of the source data files. (The geometric means were weighted by the annual number of measurements.) For lakes, data were limited and national statistics were developed, with the geometric mean of the median values being weighted by the number of measurements per year and the number of annual values in each region.

Table C-10. Surface Water Total Suspended Solids (TSS) Distributions

Hydrologic Region	Number of CCW Plants	No. of Measure-ments	No. of Annual Medians	Annual Median TSS (log triangular distribution)			Geometric Mean
				Minimum	Maximum	Weighted Geometric Mean	
1	0	9,007	33	3.2	40	8.0	6.0
2	12	47,202	38	10	316	32	40
3	37	43,395	36	6.3	79	25	25
4	14	29,577	37	6.3	794	25	25
5	43	39,900	38	4.0	100	25	25
6	6	4,137	28	5.0	316	16	20

(continued)

Surface Water Total Suspended Solids (TSS) Distributions. (continued)

Hydrologic Region	Number of CCW Plants	No. of Measure-ments	No. of Annual Medians	Annual Median TSS (log triangular distribution)			Geometric Mean
				Minimum	Maximum	Weighted Geometric Mean	
7	20	34,494	37	32	1,585	63	100
8	2	46,231	38	50	316	158	126
9	1	3,254	35	13	3,162	32	63
10	20	62,791	38	10	398	126	126
11	8	48,969	38	25	794	200	126
12	6	7,280	35	40	1,995	79	126
13	0	13,974	37	32	79,433	200	398
14	5	26,699	38	16	5,012	158	251
15	4	9,162	37	20	19,953	200	398
16	1	19,965	33	4	2,512	16	25
17	0	173,136	37	2	316	6.0	10
18	2	42,022	37	13	398	63	50
Lakes (national)	56	4,360	99	1	398	25	25

Data source: Legacy STORET database.

For **surface water pH**, the minimum, maximum, and weighted average annual median values were used to specify triangular distributions for each hydrologic region. **Table C-11** provides these regional statistics, which were applied to both rivers and lakes.

To prepare the water quality data for the source datafile, the 181 CCW disposal sites were assigned to a hydrogeologic region using a GIS. For each region, 10,000-record TSS and pH data sets were created by sampling the distributions shown in Tables C-10 and C-11. During source data file preparation, TSS data were pulled from the appropriate regional data set sequentially for each iteration at a site.

Table C-11. Regional Surface Water pH Distributions

Hydrologic Region	Number of CCW Plants	No. of Measurements	No. of Annual Median Values	Annual Median pH (triangular distribution)			Average Median pH
				Minimum	Maximum	Weighted Average	
1	0	232,025	38	5.9	7.7	6.5	6.8
2	12	447,166	39	7.2	7.6	7.4	7.4
3	37	1,595,237	39	6.3	7.2	7.0	7.0
4	14	335,261	39	7.6	8.2	8.1	8.0
5	43	684,235	41	3.5	7.5	7.2	7.1
6	6	382,915	39	6.3	7.7	7.2	7.4

(continued)

Regional Surface Water pH Distributions. (continued)

Hydrologic Region	Number of CCW Plants	No. of Measurements	No. of Annual Median Values	Annual Median pH (triangular distribution)			Average Median pH
				Minimum	Maximum	Weighted Average	
7	20	234,589	39	7.6	8.1	7.9	7.8
8	2	171,643	39	6.9	7.8	7.1	7.2
9	1	23,038	38	7.5	8.4	7.9	7.9
10	20	269,570	39	7.6	8.2	8.0	8.0
11	8	311,768	39	7.4	8.1	7.8	7.8
12	6	178,990	39	7.0	7.9	7.8	7.6
13	0	35,355	39	7.0	8.1	8.0	7.9
14	5	77,041	39	7.9	8.3	8.1	8.1
15	4	75,145	38	7.7	8.3	8.0	8.0
16	1	68,581	38	7.5	8.3	8.0	8.0
17	0	293,909	39	6.9	8.0	7.5	7.4
18	2	182,049	38	7.4	8.6	7.8	7.8

Data source: Legacy STORET database.

C.6.4 Distance to Surface Water

Because the CCW plant locations were not accurate in terms of locating the WMUs, a national empirical distribution of distances between the WMU and the nearest downgradient surface waterbodies (discussed in **Section C.2.1**) was developed using manual measurements on online maps and aerial photographs for a random selection of 30 CCW landfills and 29 CCW surface impoundments. Scaled USGS maps and aerial photographs were obtained from the Terraserver Web site (http://www.terraserver.com) by entering each plant's longitude and latitude. Labels on the maps, features on the photographs, and best professional judgment were used to identify the power plant and the surface impoundment or landfill in question, along with the nearest downgradient waterbody.

The nearest waterbody matching one of the following descriptions was used in the analysis:

- Lakes or rivers beyond the facility boundary
- Streams originating in or passing through the facility boundary and then coursing downstream beyond the property boundary
- Streams with an order of 3 or greater (i.e., fishable waterbodies).

Stream order was determined by tracing the convergence of tributaries with order 1 assigned to the furthest upstream segment indicated on the map (both ephemeral and perennial streams were assigned as order 1). Topography on the map was used to determine if the waterbody was downgradient of the plant. Many CCW WMUs in the sample were located on a large waterbody.

Once the waterbody was identified, the scale provided on the maps and photos was used to measure the horizontal distance between the CCW impoundment or landfill and the waterbody. All assignments and measurements were independently checked for accuracy.

The two distributions (landfills and surface impoundments) were statistically compared using (1) a Wilcoxon Rank Sum Test (to determine whether one distribution is shifted to the right or left of the other distribution) and (2) a Quantile Test (to test for differences, that is, differing numbers of observations) between the two distributions for the values above a given percentile. The results of the Wilcoxon test showed a p value of 0.64, indicating no significant difference in the shape of the distributions. The Quantile Test evaluated every decile from 0.1 to 0.9, with adjustments to the lower percentiles to be estimated for large numbers of ties in the ranks for the lower end of the data. The nonsignificant p values ranged from 0.33 (for 90th percentile) to 0.17 (for the 40th percentile). One significant p value indicating differences between the two distributions occurred at the 17th percentile (p value = 0.066), but the remainder of the tests showed no significant differences. Based on these results, the distributions were judged to be similar and combined to produce the single distribution of 59 values used to produce a single empirical distribution (previously shown in Table C-2) that was applied nationally to both landfills and surface impoundments at the CCW sites.

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Attachment C-1: Soil Data

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
A B Brown	43.9	SCL	6.0	1.2
A B Brown	51.1	SLT	6.5	1.6
A B Brown	5.0	SNL	6.9	1.4
A/C Power- Ace Operations	8.9	SCL	8.9	0.21
A/C Power- Ace Operations	32.0	SLT	8.4	0.46
A/C Power- Ace Operations	59.1	SNL	8.0	0.46
Allen	48.9	SCL	7.1	0.98
Allen	19.2	SLT	6.2	1.1
Allen	32.0	SNL	7.1	1.1
Alma	18.9	SCL	6.6	1.7
Alma	59.4	SLT	6.5	3.4
Alma	21.7	SNL	5.6	0.69
Antelope Valley	8.4	SCL	7.6	3.2
Antelope Valley	68.5	SLT	7.6	1.7
Antelope Valley	23.1	SNL	7.8	2.4
Arkwright	50.7	SCL	5.4	0.5
Arkwright	24.7	SLT	5.6	0.88
Arkwright	24.5	SNL	5.4	0.64
Asheville	6.3	SCL	5.4	0.43
Asheville	77.8	SLT	5.2	0.99
Asheville	15.8	SNL	5.4	1
Baldwin	39.5	SCL	6.2	1.3
Baldwin	58.6	SLT	6.0	1.6
Baldwin	1.9	SNL	6.5	1.4
Barry	35.8	SCL	4.8	3.6
Barry	23.5	SLT	4.8	7
Barry	40.7	SNL	4.8	4.4
Bay Front	11.7	SCL	7.3	4
Bay Front	21.1	SLT	7.1	3.8
Bay Front	67.2	SNL	7.1	1.4
Bay Shore	90.8	SCL	7.1	4.1
Bay Shore	4.3	SLT	7.2	2.6
Bay Shore	4.9	SNL	7.7	9.3
Belews Creek	69.2	SCL	5.2	0.34
Belews Creek	14.0	SLT	5.4	1

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Belews Creek	16.8	SNL	5.2	0.4
Ben French	25.3	SCL	8.0	0.87
Ben French	59.7	SLT	7.7	1.8
Ben French	15.0	SNL	7.1	1.7
Big Cajun 2	66.4	SCL	7.1	1.1
Big Cajun 2	28.4	SLT	6.3	1.2
Big Cajun 2	5.2	SNL	6.0	1.3
Big Sandy	54.8	SCL	5.4	1.6
Big Sandy	41.5	SLT	5.3	1.9
Big Sandy	3.7	SNL	5.1	2.6
Big Stone	7.3	SCL	7.5	5.7
Big Stone	45.0	SLT	7.7	3.1
Big Stone	47.7	SNL	7.5	1.1
Black Dog Steam Plant	8.2	SCL	6.9	4.2
Black Dog Steam Plant	41.4	SLT	6.8	2.5
Black Dog Steam Plant	50.4	SNL	6.9	1.8
Blue Valley	63.8	SCL	6.3	1.5
Blue Valley	31.6	SLT	6.6	2.8
Blue Valley	4.6	SNL	6.5	1.1
Bowen	18.1	SCL	5.0	1.2
Bowen	81.9	SLT	5.0	0.74
Brandon Shores	18.2	SCL	4.5	0.47
Brandon Shores	16.8	SLT	4.6	3.4
Brandon Shores	64.9	SNL	4.8	0.88
Buck	79.1	SCL	5.4	0.39
Buck	18.9	SLT	5.6	1
Buck	2.0	SNL	5.3	0.6
Bull Run	76.7	SCL	5.2	0.92
Bull Run	18.2	SLT	5.6	1.7
Bull Run	5.1	SNL	5.0	0.67
C D McIntosh Jr	6.5	SCL	8.1	2.3
C D McIntosh Jr	93.5	SNL	5.5	1.8
C P Crane	34.1	SCL	4.8	0.52
C P Crane	34.3	SLT	4.7	1
C P Crane	31.6	SNL	4.9	1.1
Cape Fear	67.6	SCL	5.1	0.97
Cape Fear	24.7	SLT	5.4	1.5
Cape Fear	7.7	SNL	5.2	0.66
Carbon	0.4	SCL	6.3	7.4

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Carbon	95.8	SLT	7.8	3.4
Carbon	3.8	SNL	8.2	1.4
Cardinal	69.1	SCL	5.8	1
Cardinal	30.4	SLT	5.7	1.7
Cardinal	0.5	SNL	6.4	2
Cayuga	32.3	SCL	6.6	1.9
Cayuga	48.7	SLT	7.1	1.4
Cayuga	19.0	SNL	6.8	1.1
Chalk Point	6.9	SCL	4.6	0.58
Chalk Point	16.4	SLT	4.8	8.8
Chalk Point	76.7	SNL	4.6	1.1
Cholla	27.3	SCL	8.4	1.9
Cholla	61.0	SLT	8.1	0.62
Cholla	11.6	SNL	8.3	0.75
Cliffside	66.4	SCL	5.2	0.31
Cliffside	13.6	SLT	5.5	0.77
Cliffside	20.0	SNL	5.2	0.27
Clover	71.0	SCL	5.3	0.71
Clover	23.3	SLT	5.3	1.3
Clover	5.7	SNL	5.1	0.65
Coal Creek	6.1	SCL	6.8	3
Coal Creek	82.7	SLT	7.6	1.7
Coal Creek	11.2	SNL	8.2	2.8
Coleto Creek	12.1	SCL	7.0	1.1
Coleto Creek	86.0	SLT	7.4	0.78
Coleto Creek	1.8	SNL	6.2	0.75
Colstrip	9.0	SCL	8.0	0.79
Colstrip	63.0	SLT	8.2	0.73
Colstrip	27.9	SNL	8.3	0.54
Conemaugh	11.8	SCL	5.0	2.7
Conemaugh	81.4	SLT	4.8	1.3
Conemaugh	6.8	SNL	4.5	1.8
Conesville	44.0	SCL	5.4	2.2
Conesville	45.5	SLT	5.6	1.9
Conesville	10.5	SNL	5.0	2.2
Council Bluffs	43.3	SCL	7.5	1.5
Council Bluffs	47.2	SLT	7.6	1.2
Council Bluffs	9.6	SNL	7.7	0.74
Crawford	48.4	SCL	6.8	1.9

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Crawford	23.6	SLT	6.7	1.4
Crawford	28.0	SNL	6.7	0.82
Crist	18.8	SCL	5.4	4.5
Crist	32.3	SLT	5.3	1.1
Crist	48.8	SNL	5.4	3.3
Cross	3.0	SCL	5.0	1.3
Cross	46.0	SLT	4.6	0.58
Cross	51.0	SNL	4.9	1.2
Cumberland	61.1	SCL	5.3	1.6
Cumberland	34.2	SLT	5.7	0.98
Cumberland	4.8	SNL	5.2	1.3
Dale	91.7	SCL	6.4	1.9
Dale	8.2	SLT	6.4	2
Dale	0.1	SNL	6.7	1.3
Dallman	66.2	SCL	6.4	1.8
Dallman	33.3	SLT	6.7	1.2
Dallman	0.5	SNL	7.0	1.1
Dan E Karn	0.01	SCL	7.0	3
Dan E Karn	53.6	SLT	7.9	4.2
Dan E Karn	46.3	SNL	7.8	5.4
Dan River	73.3	SCL	5.0	0.39
Dan River	12.0	SLT	5.3	1.4
Dan River	14.7	SNL	5.1	0.6
Danskammer	89.8	SLT	5.8	2.9
Danskammer	10.2	SNL	6.9	2.8
Dave Johnston	2.2	SCL	8.9	0.96
Dave Johnston	36.6	SLT	8.2	1.2
Dave Johnston	61.2	SNL	8.2	1.1
Dickerson	6.1	SCL	5.1	0.52
Dickerson	93.9	SLT	5.2	0.68
Dolet Hills	65.7	SCL	4.8	0.97
Dolet Hills	21.6	SLT	5.0	0.77
Dolet Hills	12.7	SNL	5.1	1.1
Duck Creek	65.5	SCL	6.4	0.82
Duck Creek	33.6	SLT	6.5	0.6
Duck Creek	0.9	SNL	7.0	0.98
Dunkirk	8.8	SCL	7.3	5.4
Dunkirk	79.6	SLT	6.9	4.6
Dunkirk	11.6	SNL	6.5	2.7

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
E D Edwards	49.5	SCL	6.4	1.1
E D Edwards	29.8	SLT	6.3	1.2
E D Edwards	20.6	SNL	6.8	1.1
E W Brown	92.9	SCL	6.4	3.7
E W Brown	7.1	SLT	6.6	3.8
Eckert Station	4.8	SCL	7.2	4.5
Eckert Station	82.0	SLT	6.9	1.2
Eckert Station	13.2	SNL	6.7	0.5
Edgewater	58.5	SCL	7.3	3.3
Edgewater	3.7	SLT	7.3	1.2
Edgewater	37.8	SNL	6.8	2.2
Elmer W Stout	29.9	SCL	6.7	1.9
Elmer W Stout	56.7	SLT	7.0	1.2
Elmer W Stout	13.3	SNL	6.8	0.8
F B Culley	45.3	SCL	5.9	0.93
F B Culley	48.9	SLT	6.5	2
F B Culley	5.8	SNL	6.9	1.1
Fayette Power Prj	51.9	SCL	7.7	3.8
Fayette Power Prj	35.7	SLT	7.6	1.2
Fayette Power Prj	12.5	SNL	7.1	1
Flint Creek	62.2	SCL	4.9	0.87
Flint Creek	37.8	SLT	5.3	0.69
Fort Martin	45.9	SCL	5.6	1.2
Fort Martin	54.1	SLT	5.2	1.9
Fort Martin	0.04	SNL	4.6	2.5
Frank E Ratts	30.9	SCL	5.8	1.5
Frank E Ratts	58.0	SLT	6.3	1.1
Frank E Ratts	11.1	SNL	7.0	0.73
G G Allen	85.9	SCL	5.3	0.36
G G Allen	11.9	SLT	5.6	1.1
G G Allen	2.2	SNL	5.2	0.28
Gadsden	45.2	SCL	4.8	0.68
Gadsden	46.4	SLT	5.3	1.3
Gadsden	8.5	SNL	5.1	0.97
Gallatin	56.1	SCL	5.6	0.94
Gallatin	43.9	SLT	5.4	0.94
Gen J M Gavin	35.9	SCL	6.0	1.4
Gen J M Gavin	46.1	SLT	5.6	2.1
Gen J M Gavin	18.0	SNL	5.1	1.3

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Genoa	14.3	SCL	6.1	2.3
Genoa	64.6	SLT	6.6	1.8
Genoa	21.0	SNL	6.1	0.97
Gibson	55.3	SCL	6.6	1.5
Gibson	43.2	SLT	6.4	1.1
Gibson	1.5	SNL	7.3	0.67
Gorgas	17.0	SCL	4.6	0.42
Gorgas	53.0	SLT	5.1	0.77
Gorgas	30.0	SNL	5.2	0.73
Green River	48.4	SCL	5.9	1
Green River	51.6	SLT	6.0	1.4
Greene County	19.5	SCL	5.1	1.8
Greene County	72.6	SLT	5.2	1.4
Greene County	7.9	SNL	4.9	1.6
H B Robinson	0.1	SCL	5.2	0.75
H B Robinson	32.6	SLT	4.8	1
H B Robinson	67.3	SNL	5.3	0.6
Hammond	54.7	SCL	5.1	0.74
Hammond	33.8	SLT	5.3	1.3
Hammond	11.5	SNL	5.0	0.75
Harllee Branch	54.7	SCL	5.3	0.49
Harllee Branch	15.3	SLT	5.6	0.97
Harllee Branch	30.0	SNL	5.3	0.47
Harrison	48.8	SCL	5.6	1
Harrison	51.2	SLT	5.0	2.1
Hatfield's Ferry	39.3	SCL	5.7	1.8
Hatfield's Ferry	60.4	SLT	5.3	1.6
Hatfield's Ferry	0.3	SNL	4.6	2.5
Hennepin	44.6	SCL	6.4	1.5
Hennepin	38.2	SLT	6.7	1.1
Hennepin	17.2	SNL	7.0	1.3
Heskett	39.9	SCL	8.0	2.1
Heskett	44.1	SLT	7.6	2.4
Heskett	16.0	SNL	7.7	1.9
Holcomb	4.4	SLT	7.9	0.67
Holcomb	95.6	SNL	7.3	0.75
Homer City	11.0	SCL	4.9	2.9
Homer City	84.5	SLT	4.8	1.6
Homer City	4.5	SNL	4.5	2.1

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Hoot Lake	3.1	SCL	7.5	5.4
Hoot Lake	38.9	SLT	7.7	2.6
Hoot Lake	58.1	SNL	7.5	1.3
Hugo	55.1	SCL	6.6	1.4
Hugo	35.8	SLT	6.7	1.6
Hugo	9.2	SNL	5.3	0.7
Hunter	90.8	SCL	8.3	0.73
Hunter	3.5	SLT	8.2	2
Hunter	5.7	SNL	8.5	0.75
Huntington	4.5	SCL	8.6	1.5
Huntington	79.5	SLT	8.0	2.4
Huntington	15.9	SNL	8.6	1.3
Intermountain	46.9	SCL	8.6	0.7
Intermountain	8.3	SLT	8.9	0.51
Intermountain	44.8	SNL	8.8	0.44
J H Campbell	5.0	SLT	7.1	1.8
J H Campbell	95.0	SNL	5.9	1.2
J M Stuart	73.5	SCL	6.5	1.6
J M Stuart	24.8	SLT	6.8	2.4
J M Stuart	1.7	SNL	5.5	2
J R Whiting	80.6	SCL	7.1	4.2
J R Whiting	17.1	SLT	7.1	2.1
J R Whiting	2.3	SNL	6.8	2.8
Jack McDonough	58.9	SCL	5.2	0.46
Jack McDonough	7.8	SLT	5.6	1.1
Jack McDonough	33.3	SNL	5.3	0.37
Jack Watson	20.5	SCL	6.7	11
Jack Watson	46.8	SLT	4.8	3
Jack Watson	32.8	SNL	4.9	3.8
James H Miller Jr	17.0	SCL	4.6	0.42
James H Miller Jr	53.0	SLT	5.1	0.77
James H Miller Jr	30.0	SNL	5.2	0.73
Jim Bridger	1.4	SCL	8.7	0.75
Jim Bridger	37.9	SLT	8.6	0.52
Jim Bridger	60.6	SNL	8.2	0.64
John E Amos	35.8	SCL	6.3	1.6
John E Amos	64.2	SLT	5.1	2.2
John Sevier	43.2	SCL	6.2	1.6
John Sevier	56.7	SLT	5.8	1.2

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
John Sevier	0.2	SNL	5.0	0.67
Johnsonville	39.2	SCL	5.1	1.7
Johnsonville	57.3	SLT	5.2	1.3
Johnsonville	3.5	SNL	4.7	1.5
Joliet 29	52.8	SCL	7.1	2.7
Joliet 29	43.5	SLT	7.0	2.1
Joliet 29	3.7	SNL	7.1	1.8
Keystone	7.7	SCL	4.9	2.8
Keystone	90.1	SLT	4.9	1.4
Keystone	2.2	SNL	4.5	2.2
Killen Station	74.3	SCL	6.0	1.9
Killen Station	24.0	SLT	6.3	2.2
Killen Station	1.8	SNL	6.2	1.7
Kingston	66.7	SCL	5.0	1.2
Kingston	21.0	SLT	5.5	1.7
Kingston	12.3	SNL	5.0	0.67
Kraft	57.1	SCL	7.2	11
Kraft	22.8	SLT	5.0	1.3
Kraft	20.1	SNL	5.0	1.4
L V Sutton	18.0	SCL	6.1	3.9
L V Sutton	32.4	SLT	5.0	3.7
L V Sutton	49.6	SNL	5.0	1.6
Lansing	9.0	SCL	5.8	2.6
Lansing	67.7	SLT	6.8	2.1
Lansing	23.3	SNL	6.2	1.4
Laramie R Station	41.1	SLT	8.1	0.87
Laramie R Station	58.9	SNL	7.9	1.2
Lawrence EC	51.5	SCL	6.6	1.9
Lawrence EC	47.7	SLT	6.8	2.9
Lawrence EC	0.8	SNL	7.5	0.75
Lee	16.4	SCL	5.0	1.3
Lee	51.1	SLT	5.0	1.3
Lee	32.5	SNL	5.1	0.96
Leland Olds	13.5	SCL	7.8	2.6
Leland Olds	52.9	SLT	7.6	1.9
Leland Olds	33.6	SNL	7.5	2
Lon Wright	25.7	SCL	7.5	1.5
Lon Wright	8.4	SLT	7.0	2.1
Lon Wright	65.9	SNL	7.8	1.4

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Louisa	35.5	SCL	6.7	1.8
Louisa	16.6	SLT	6.3	1.5
Louisa	47.9	SNL	6.6	0.96
Marion	10.9	SCL	5.6	0.96
Marion	88.8	SLT	5.2	0.95
Marion	0.3	SNL	6.6	1
Marshall	72.1	SCL	5.2	0.33
Marshall	12.9	SLT	5.5	0.87
Marshall	15.0	SNL	5.2	0.27
Martin Lake	34.3	SCL	4.9	1
Martin Lake	25.1	SLT	5.1	0.8
Martin Lake	40.6	SNL	5.1	0.73
Mayo	71.9	SCL	5.6	0.61
Mayo	27.9	SLT	5.6	1
Mayo	0.2	SNL	5.2	0.76
Meramec	87.9	SCL	6.4	1.3
Meramec	12.1	SLT	6.5	1.3
Merom	30.2	SCL	5.5	0.84
Merom	59.2	SLT	5.8	0.96
Merom	10.6	SNL	6.4	0.77
Miami Fort	69.6	SCL	6.5	1.7
Miami Fort	27.3	SLT	6.8	2
Miami Fort	3.1	SNL	6.7	1.2
Milton R Young	4.6	SCL	7.6	3.1
Milton R Young	92.9	SLT	7.7	1.5
Milton R Young	2.5	SNL	7.5	1.8
Mitchell - PA	19.1	SCL	5.9	2.1
Mitchell - PA	80.9	SLT	5.5	1.4
Mitchell - WV	39.9	SCL	6.0	1.7
Mitchell - WV	59.9	SLT	5.2	2
Mitchell - WV	0.2	SNL	6.0	1.3
Mohave	29.0	SLT	8.1	0.26
Mohave	71.0	SNL	8.1	0.31
Monroe	38.5	SCL	7.0	3
Monroe	49.5	SLT	7.2	3.1
Monroe	12.0	SNL	6.8	3.5
Morgantown	21.7	SCL	4.6	1.2
Morgantown	39.3	SLT	4.7	3.2
Morgantown	39.0	SNL	4.9	1.3

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Mountaineer (1301)	56.1	SCL	6.0	1.6
Mountaineer (1301)	34.2	SLT	5.9	2.2
Mountaineer (1301)	9.8	SNL	4.9	2.5
Mt Storm	4.1	SCL	5.0	2.9
Mt Storm	65.3	SLT	4.7	1.4
Mt Storm	30.6	SNL	4.4	1
Muscatine Plant #1	46.8	SCL	6.6	1.8
Muscatine Plant #1	27.4	SLT	6.4	1.4
Muscatine Plant #1	25.8	SNL	6.6	0.84
Muskogee	30.9	SCL	6.5	1.7
Muskogee	53.1	SLT	6.8	1.1
Muskogee	16.0	SNL	6.7	1
Neal North	36.7	SCL	7.9	1.1
Neal North	46.5	SLT	7.9	0.67
Neal North	16.9	SNL	7.7	0.73
Neal South	34.0	SCL	7.8	1.1
Neal South	50.7	SLT	7.8	0.69
Neal South	15.3	SNL	7.7	0.73
Nebraska City	55.5	SCL	7.4	1.4
Nebraska City	35.5	SLT	7.3	1.7
Nebraska City	9.0	SNL	7.7	0.74
New Castle	5.1	SCL	7.7	0.73
New Castle	81.6	SLT	5.9	2.8
New Castle	13.2	SNL	6.1	1.5
Newton	37.9	SCL	5.5	0.54
Newton	61.3	SLT	5.5	0.53
Newton	0.7	SNL	6.5	0.85
North Omaha	29.0	SCL	7.4	1.5
North Omaha	60.1	SLT	7.7	0.82
North Omaha	11.0	SNL	7.7	0.74
Northeastern	76.9	SCL	6.7	2.1
Northeastern	21.3	SLT	6.3	2.2
Northeastern	1.8	SNL	5.6	2
Nucla	61.2	SLT	7.9	0.98
Nucla	38.8	SNL	8.1	0.55
Oklaunion	92.2	SCL	8.0	1.7
Oklaunion	7.0	SLT	7.9	0.94
Oklaunion	0.7	SNL	7.3	1.5
Paradise	14.8	SCL	5.6	1.4

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Paradise	85.2	SLT	5.9	1.2
Petersburg	29.7	SCL	5.9	1.5
Petersburg	62.9	SLT	6.3	1.2
Petersburg	7.5	SNL	7.2	0.59
Pleasant Prairie	97.2	SCL	7.1	1.7
Pleasant Prairie	2.8	SNL	7.3	1.5
Port Washington	86.3	SCL	7.3	3.3
Port Washington	7.7	SLT	7.5	0.68
Port Washington	6.1	SNL	7.3	3
Portland	8.7	SCL	5.8	0.58
Portland	90.8	SLT	5.5	1.1
Portland	0.5	SNL	6.0	1.8
Possum Point	6.3	SCL	4.6	0.58
Possum Point	43.0	SLT	4.9	3
Possum Point	50.7	SNL	4.9	0.8
Potomac River	13.3	SCL	4.5	0.56
Potomac River	35.5	SLT	4.9	2.8
Potomac River	51.2	SNL	5.0	1.1
Presque Isle	18.7	SLT	5.2	2.5
Presque Isle	81.3	SNL	5.3	3.1
R Gallagher	40.4	SCL	5.6	1.5
R Gallagher	59.0	SLT	5.9	2.1
R Gallagher	0.5	SNL	6.9	1.4
R M Schahfer	2.1	SCL	7.1	3.8
R M Schahfer	6.5	SLT	6.9	2.9
R M Schahfer	91.4	SNL	6.6	1.5
Reid Gardner	13.3	SCL	8.4	0.29
Reid Gardner	21.6	SLT	8.3	0.58
Reid Gardner	65.1	SNL	8.4	0.34
Richard Gorsuch	69.9	SCL	6.1	1.7
Richard Gorsuch	27.0	SLT	5.9	2.4
Richard Gorsuch	3.0	SNL	5.1	2.6
Riverbend	77.4	SCL	5.3	0.37
Riverbend	20.1	SLT	5.7	1.1
Riverbend	2.5	SNL	5.2	0.45
Rodemacher	42.9	SCL	6.5	0.96
Rodemacher	51.4	SLT	6.5	0.92
Rodemacher	5.7	SNL	5.3	0.85
Roxboro	40.3	SCL	5.5	0.47

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Roxboro	55.7	SLT	6.0	0.79
Roxboro	4.0	SNL	5.5	1.4
Sandow	0.8	SCL	6.9	0.5
Sandow	37.4	SLT	6.3	0.66
Sandow	61.8	SNL	6.3	0.64
Scherer	58.5	SCL	5.3	0.39
Scherer	12.8	SLT	5.5	0.97
Scherer	28.7	SNL	5.3	0.42
Shawnee	9.5	SCL	5.8	1
Shawnee	84.2	SLT	5.6	1.4
Shawnee	6.3	SNL	6.5	1.1
Shawville	5.2	SCL	5.0	3
Shawville	82.6	SLT	4.9	1.1
Shawville	12.2	SNL	4.4	1.2
Sheldon	62.7	SCL	6.8	2.3
Sheldon	33.2	SLT	7.0	1.6
Sheldon	4.1	SNL	6.9	2
South Oak Creek	95.5	SCL	7.1	1.9
South Oak Creek	4.5	SNL	7.3	1.6
Springerville	10.0	SLT	8.1	0.79
Springerville	90.0	SNL	7.9	0.79
St Johns River Power	27.1	SCL	6.9	49
St Johns River Power	0.4	SLT	5.0	1.3
St Johns River Power	72.5	SNL	5.2	1.1
Stanton Energy Ctr	0.8	SCL	7.0	10
Stanton Energy Ctr	2.4	SLT	7.7	1
Stanton Energy Ctr	96.8	SNL	5.3	4.8
Stockton Cogen Company	89.9	SCL	7.6	1.8
Stockton Cogen Company	6.6	SLT	7.5	1.5
Stockton Cogen Company	3.5	SNL	6.8	0.51
Syl Laskin	8.5	SCL	6.5	3.2
Syl Laskin	4.6	SLT	6.3	6.3
Syl Laskin	86.9	SNL	5.8	3.1
Tecumseh EC	55.2	SCL	6.6	2
Tecumseh EC	41.9	SLT	6.9	2.6
Tecumseh EC	2.9	SNL	7.6	0.62
Texas-New Mexico	4.4	SCL	7.0	0.61
Texas-New Mexico	43.5	SLT	6.3	0.67
Texas-New Mexico	52.1	SNL	6.0	0.77

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Titus	31.8	SCL	6.0	0.76
Titus	63.6	SLT	5.6	1.4
Titus	4.6	SNL	5.0	0.98
Trimble County	57.3	SCL	6.3	2
Trimble County	41.9	SLT	6.5	1.9
Trimble County	0.8	SNL	5.9	1.7
Tyrone	92.1	SCL	6.3	3.7
Tyrone	7.9	SLT	6.6	3.9
Valley	98.5	SCL	6.9	1.2
Valley	0.2	SLT	7.5	0.45
Valley	1.3	SNL	7.4	1.3
Vermilion	82.5	SCL	6.9	1.3
Vermilion	16.6	SLT	7.0	1.2
Vermilion	0.8	SNL	7.2	1.1
Victor J Daniel Jr	46.2	SCL	4.6	2.2
Victor J Daniel Jr	27.7	SLT	4.7	2.3
Victor J Daniel Jr	26.1	SNL	4.7	16
W A Parish	95.8	SCL	7.4	1.4
W A Parish	4.2	SLT	7.9	0.74
W H Weatherspoon	7.4	SCL	5.5	1.9
W H Weatherspoon	50.4	SLT	4.7	2.2
W H Weatherspoon	42.2	SNL	4.8	1.3
W S Lee	68.0	SCL	5.3	0.48
W S Lee	9.0	SLT	5.7	1
W S Lee	23.0	SNL	5.3	0.41
Wabash River	22.0	SCL	6.4	1.6
Wabash River	48.5	SLT	6.9	1.2
Wabash River	29.5	SNL	6.7	1.2
Walter C Beckjord	71.6	SCL	6.3	1.4
Walter C Beckjord	26.5	SLT	6.7	2
Walter C Beckjord	1.9	SNL	6.6	1.1
Wansley	46.3	SCL	5.2	0.52
Wansley	18.1	SLT	5.6	1.2
Wansley	35.5	SNL	5.4	0.5
Warrick	45.8	SCL	6.0	0.95
Warrick	48.6	SLT	6.5	1.9
Warrick	5.6	SNL	7.0	1.1
Waukegan	43.9	SCL	6.6	1
Waukegan	18.1	SLT	6.6	1.4

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Waukegan	38.0	SNL	6.7	0.8
Weston	33.5	SLT	5.6	1.7
Weston	66.5	SNL	6.0	1.4
Widows Creek	64.5	SCL	5.3	0.88
Widows Creek	20.0	SLT	5.2	1.4
Widows Creek	15.5	SNL	5.4	1.2
Will County	40.0	SCL	6.8	1.8
Will County	52.7	SLT	7.0	0.96
Will County	7.2	SNL	7.1	0.98
Wyodak	1.3	SCL	8.1	0.38
Wyodak	40.2	SLT	7.9	1.1
Wyodak	58.5	SNL	7.9	0.93
Yates	47.8	SCL	5.2	0.48
Yates	17.7	SLT	5.6	1.2
Yates	34.5	SNL	5.3	0.48

Attachment C-2: Hydrogeologic Environment

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Big Cajun 2	10Ba	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Predominant alluvial setting (100% alluvium); soils have significant fines (SCL+SLT = 95%)
A B Brown	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Predominant alluvial setting; soils have significant fines (SCL+SLT = 95%)
A/C Power-Ace Operations	2C	Alluvial Fans	5	Alluvial Basins Valleys and Fans	100	Based on surficial geology; consistent with alluvial fan setting
Allen	10Ba	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Setting based on aquifer coverages, surficial geology; Heath (1985) and soils indicate overbank deposits
Alma	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	50	Percentage based on SNL/SCL soils; setting based on productive aquifers and surficial geology
Alma	7Eb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	50	Percentage based on SNL/SCL soils; setting based on productive aquifers and surficial geology
Antelope Valley	7G	Thin Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	100	Based on principal aquifer and surficial geology coverages
Arkwright	8D	Regolith	1	Metamorphic and Igneous	100	Most common Piedmont setting (residuum)
Asheville	8B	Alluvial Mountain Valleys	5	Alluvial Basins Valleys and Fans	100	Appropriate for alluvial blue ridge valley (colluvium)
Baldwin	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	70	Percentage based on surficial geology (74% Floodplain and alluvium gravel terraces)
Baldwin	7G	Thin Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	30	Percentage based on surficial geology (74% Floodplain and alluvium gravel terraces)

(continued)

Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Barry	10Ba	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Predominant alluvial setting, significant fine grained soils = overbank deposits
Bay Front	7Bb	Outwash Over Bedded Sedimentary Rock	2	Bedded Sedimentary Rock	70	Percentage based on productive aquifers
Bay Front	7D	Buried Valley	4	Sand and Gravel	30	Percentage based on productive aquifers
Bay Shore	7Ac	Glacial Till Over Solution Limestone	12	Solution Limestone	100	Closest setting considering carbonate aquifers, high SCL soils, and lake deposits surficial geology
Belews Creek	6H	Triassic Basins	2	Bedded Sedimentary Rock	50	Sources somewhat dissimilar; fraction based on surficial geology; Triassic basin
Belews Creek	8D	Regolith	1	Metamorphic and Igneous	50	Sources somewhat dissimilar; fraction based on surficial geology
Ben French	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	60	Percentage, thin soils based on surficial geology
Ben French	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	40	Percentage based on surficial geology; significant fine soils (25% SCL)
Big Sandy	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	50	Percentage based on surficial geology; thin soils inferred from colluvium
Big Sandy	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	50	Percentage based on surficial geology; soils have significant fines (SCL+SLT = 95%)
Big Stone	7Ba	Outwash	8	Outwash	100	Based on surficial geology
Black Dog Steam Plant	7Bb	Outwash Over Bedded Sedimentary Rock	2	Bedded Sedimentary Rock	100	Based on surficial geology, aquifer coverages
Blue Valley	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	80	Percentage based on Heath (1985), productive aquifers

(continued)

Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Blue Valley	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	20	Percentage based on Heath (1985), productive aquifers
Bowen	6Db	Alternating Sandstone, Limestone and Shale - Deep Regolith	2	Bedded Sedimentary Rock	100	Based on aquifers, surficial residuum (massive red clay); metamorphic surficial geology not consistent with Valley and Ridge
Brandon Shores	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Assigned based on location and aquifer and surficial geology coverages; Heath region incorrect (it's Atlantic Coastal Plain, not Piedmont)
Buck	8E	River Alluvium	6	River Valleys and Floodplains with Overbank Deposit	100	Based on productive aquifer & Heath region coverages
Bull Run	6Db	Alternating Sandstone, Limestone and Shale - Deep Regolith	2	Bedded Sedimentary Rock	60	Percentage based on surficial geology
Bull Run	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	40	Percentage based on surficial geology; high SCL (77%) = overbank deposits
C D McIntosh Jr	11A	Solution Limestone and Shallow Surficial Aquifers	12	Solution Limestone	100	Based on both aquifer coverages
C P Crane	10Aa	Regional Aquifers	4	Sand and Gravel	50	Appears to be on border between Piedmont and Coastal Plain
C P Crane	8D	Regolith	1	Metamorphic and Igneous	50	Appears to be on border between Piedmont and Coastal Plain
Cape Fear	6H	Triassic Basins	2	Bedded Sedimentary Rock	20	Percentage based on productive aquifer & Heath region coverages; Triassic basin
Cape Fear	8E	River Alluvium	6	River Valleys and Floodplains with Overbank Deposit	80	Percentage based on productive aquifer & Heath region coverages
Carbon	4B	Consolidated Sedimentary Rock	2	Bedded Sedimentary Rock	100	Setting based on aquifer and surficial geology coverages

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Cardinal	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	30	Percentage based on surficial geology; soils with low (<1%) SNL
Cardinal	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	70	Percentage based on surficial geology; soils with low (<1%) SNL
Cayuga	7D	Buried Valley	4	Sand and Gravel	100	Glaciofluvial aquifer overlaid by alluvial deposits
Chalk Point	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Predominant setting
Cholla	4B	Consolidated Sedimentary Rock	2	Bedded Sedimentary Rock	20	Percentage based on surficial geology (83% Floodplain and alluvium gravel terraces)
Cholla	4C	River Alluvium	7	River Valleys and Floodplains without Overbank Deposits	80	Percentage based on surficial geology (83% Floodplain and alluvium gravel terraces)
Cliffside	8D	Regolith	1	Metamorphic and Igneous	100	Based on surficial geology
Clover	6H	Triassic Basins	2	Bedded Sedimentary Rock	20	Percentage based on surficial geology; Triassic Basin from Heath (1985) and principal aquifer coverage
Clover	8E	River Alluvium	6	River Valleys and Floodplains with Overbank Deposit	80	Percentage based on surficial geology
Coal Creek	7G	Thin Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	100	Based on principal aquifer and surficial geology coverages
Coleto Creek	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Setting based on aquifer and surficial geology coverages
Colstrip	6da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	100	Based on all coverages

(continued)

Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Conemaugh	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	100	Setting based on aquifer coverages & Heath (1985); thin regolith inferred from colluvium
Conesville	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	40	Percentage based on surficial geology; soils with low (10%) SNL
Conesville	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	60	Percentage based on surficial geology; soils with low (10%) SNL
Council Bluffs	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Setting based on productive aquifers
Crawford	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Assigned based on predominant surficial geology (98% Floodplain and alluvium gravel terraces), productive aquifer coverage
Crist	10Bb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	100	Assigned based on predominant surficial geology (96% Floodplain and alluvium gravel terraces), coarse-grained soil (49% SNL)
Cross	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Setting based on aquifers, surficial geology, soils, Heath (1985)
Cumberland	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Setting based on surface geology; high (61%) SCL = overbank deposits
Dale	6E	Solution Limestone	12	Solution Limestone	20	Percentage based on surficial geology; setting from principal aquifers (carbonate)
Dale	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	80	Percentage based on surficial geology; soils have significant fines (SNL = 0.1%)
Dallman	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	100	Based on soils, surficial geology, principal aquifer
Dan E Karn	7F	Glacial Lake Deposits	4	Sand and Gravel	100	Based on surficial geology, soils

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Dan River	6H	Triassic Basins	2	Bedded Sedimentary Rock	100	Based on surfucial geology, principal aquifers; Triassic basin
Danskammer	7D	Buried Valley	4	Sand and Gravel	100	Based on predominant Heath region, productive aquifers; little coarse-grained soils
Dave Johnston	4C	River Alluvium	7	River Valleys and Floodplains without Overbank Deposits	100	Based on aquifer and surficial geology coverages, Heath (1985)
Dickerson	8D	Regolith	1	Metamorphic and Igneous	100	Predominant setting
Dolet Hills	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Predominant shallow unconsolidated aquifer system
Duck Creek	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Assigned based on predominant surficial geology (100% Floodplain and alluvium gravel terraces), Heath Alluvial Valley Region
Dunkirk	7H	Beaches, Beach Ridges and Sand Dunes	11	Coastal Beaches	100	Based on location, surficial geology
E D Edwards	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	20	Percentage based on surficial geology (83% Floodplain and alluvium gravel terraces)
E D Edwards	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	80	Percentage based on surficial geology (83% Floodplain and alluvium gravel terraces)
E W Brown	6E	Solution Limestone	12	Solution Limestone	20	Percentage based on surficial geology (76% alluvium, 23% clay); soils have significant fine-grained (0% SNL)
E W Brown	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	80	Percentage based on surficial geology (76% alluvium, 23% clay); soils have significant fine-grained (0% SNL)
Eckert Station	7Bb	Outwash Over Bedded Sedimentary Rock	2	Bedded Sedimentary Rock	30	Percentage based on productive aquifer coverage, Heath regions

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Eckert Station	7Eb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	70	Percentage based on productive aquifer coverage, Heath regions
Edgewater	7Bc	Outwash Over Solution Limestone	12	Solution Limestone	100	Setting based on aquifer and surficial geology coverages
Elmer W Stout	7D	Buried Valley	4	Sand and Gravel	100	Glaciofluvial aquifer overlaid by alluvial deposits
F B Culley	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Predominant alluvial setting; soils have significant fines (SCL+SLT = 94%)
Fayette Power Prj	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Setting based on aquifer and surficial geology coverages
Flint Creek	6Db	Alternating Sandstone, Limestone and Shale - Deep Regolith	2	Bedded Sedimentary Rock	100	Ozark plateau; Heath (1985) indicates dolomite, sandy dolomite, sandstone, with no indication of solutioning. Surficial geology (cherty red clay) noted as thick regolith in Aller et al. (1987)
Fort Martin	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Setting based on surficial geology; low SNL (< 1%) = overbank deposits
Frank E Ratts	7D	Buried Valley	4	Sand and Gravel	100	Glaciofluvial aquifer in alluvial valley region (99%)
G G Allen	8D	Regolith	1	Metamorphic and Igneous	100	Based on surficial geology
Gadsden	6Db	Alternating Sandstone, Limestone and Shale - Deep Regolith	2	Bedded Sedimentary Rock	30	Percentage assigned based on productive aquifer coverage
Gadsden	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	70	Percentage assigned based on productive aquifer coverage; soils have significant fines (SCL+SLT > 25%)
Gallatin	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Setting based on surface geology; high (56%) SCL = overbank deposits

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Gen J M Gavin	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Setting based on productive aquifers, surficial geology
Genoa	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	50	Percentage based on SNL/SCL soils; setting based on surficial geology and productive aquifers
Genoa	6Fb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	50	Percentage based on SNL/SCL soils; setting based on surficial geology and productive aquifers
Gibson	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Predominant alluvial setting; soils have significant fines (SCL+SLT = 99%)
Gorgas	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	30	Percentage based on surficial geology; alluvial setting with coarser soils (= no overbank deposits)
Gorgas	6Fb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	70	Percentage based on surficial geology; alluvial setting with coarser soils (= no overbank deposits)
Green River	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Predominant alluvial setting (>85% alluvium); soils have significant fines (SNL = 0%)
Greene County	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	30	Percentage based on surficial geology; soils have significant fines (SCL+SLT > 90%)
Greene County	10Ba	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	70	Percentage based on surficial geology; soils have significant fines (SCL+SLT > 90%)
H B Robinson	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Setting based on aquifers, surficial geology, soils, Heath (1985); Heath region coverage incorrect (Coastal Plain, not Piedmont)

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Hammond	6Db	Alternating Sandstone, Limestone and Shale - Deep Regolith	2	Bedded Sedimentary Rock	100	Based on aquifers, surficial residuum (massive red clay)
Harllee Branch	8E	River Alluvium	6	River Valleys and Floodplains with Overbank Deposit	100	Assigned based on predominant surficial geology (99% floodplain and alluvium gravel terraces)
Harrison	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	20	Percentage based on surficial geology; thin soils inferred from surficial geology
Harrison	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	80	Percentage based on surficial geology; 0%SNL = overbank deposits
Hatfield's Ferry	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	40	Percentage based on surficial geology; thin regolith inferred from colluvium
Hatfield's Ferry	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	60	Percentage based on surficial geology; soils < 1% SNL
Hennepin	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	30	Percentage to capture uncertainty in soils, surficial geology, principal aquifer
Hennepin	7Bb	Outwash Over Bedded Sedimentary Rock	2	Bedded Sedimentary Rock	30	Percentage to capture uncertainty in soils, surficial geology, principal aquifer
Hennepin	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	40	Percentage to capture uncertainty in soils, surficial geology, principal aquifer
Heskett	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Predominant alluvium surficial geology(96%); mixed soils
Holcomb	5Gb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	100	Alluvial valley with very coarse soils
Homer City	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	100	Setting based on aquifer coverages & Heath (1985); thin regolith inferred from colluvium

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Hoot Lake	9E	Outwash	8	Outwash	100	Based on productive aquifer, soils, surficial geology
Hugo	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	40	Percentage based on surficial geology; soil/regolith thickness inferred from Heath (1985)
Hugo	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	60	Percentage based on surficial geology; fine soils with about 10% SNL
Hunter	4B	Consolidated Sedimentary Rock	2	Bedded Sedimentary Rock	100	Setting based on aquifer and surficial geology coverages
Huntington	4B	Consolidated Sedimentary Rock	2	Bedded Sedimentary Rock	100	Setting based on aquifer and surficial geology coverages
Intermountain	2E	Playa Lakes	5	Alluvial Basins Valleys and Fans	100	Setting based on surficial geology coverage, Heath (1985)
J H Campbell	7F	Glacial Lake Deposits	4	Sand and Gravel	100	Based on surficial geology, soils
J M Stuart	6E	Solution Limestone	12	Solution Limestone	50	Percentage based on surficial geology; low (< 2%) SNL
J M Stuart	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	50	Percentage based on surficial geology; low (< 2%) SNL
J R Whiting	7F	Glacial Lake Deposits	4	Sand and Gravel	100	Based on surficial geology
Jack McDonough	8C	Mountain Flanks	2	Bedded Sedimentary Rock	100	Assigned based on predominant surficial geology (94% stony colluvium on metamorphic rocks; less silt and clay than in colluvium over limestone)
Jack Watson	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Based on all coverages
James H Miller Jr	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	20	Percentage based on surficial geology; soils have significant fines (SCL+SLT > 25%)

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
James H Miller Jr	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	80	Percentage based on surficial geology; soils have significant fines (SCL+SLT > 25%)
Jim Bridger	4B	Consolidated Sedimentary Rock	2	Bedded Sedimentary Rock	100	Based on aquifer and surficial geology coverages, Heath (1985)
John E Amos	6da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	40	Percentage based on surficial geology; thin soils inferred from surficial geology
John E Amos	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	60	Percentage based on surficial geology; 0%SNL = overbank deposits
John Sevier	6E	Solution Limestone	12	Solution Limestone	50	Percentage based on surface geology; setting based on surface geology and aquifer type, with possibility of solution limestone from Heath (1985)
John Sevier	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	50	Percentage, setting based on surface geology; low (<1%) SNL = overbank deposits
Johnsonville	6E	Solution Limestone	12	Solution Limestone	30	Percentage based on surface geology; setting based on aquifer coverages, Heath (1985); placed in Nonglaciated Central region based on aquifer coverages and Heath (1985)
Johnsonville	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	70	Percentage, setting based on surface geology; low (3%) SNL = overbank deposits; placed in Nonglaciated Central region based on aquifer coverages and Heath (1985)
Joliet 29	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	100	Based on aquifers, soils; soils don't suggest outwash like surficial geology does
Keystone	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	100	Setting based on aquifer coverages & Heath (1985); thin regolith inferred from colluvium
Killen Station	6E	Solution Limestone	12	Solution Limestone	30	Percentage based on surficial geology; low (< 2%) SNL

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Killen Station	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	70	Percentage based on surficial geology; low (< 2%) SNL
Kingston	6E	Solution Limestone	12	Solution Limestone	20	Percentage based on surface geology; setting based on surface geology and aquifer type, with possibility of solution limestone from Heath (1985)
Kingston	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	80	Percentage, setting based on surface geology; high (67 %) SCL = overbank deposits
Kraft	11A	Solution Limestone and Shallow Surficial Aquifers	12	Solution Limestone	100	Only possible assignment; predominant alluvium (84%) not well represented
L V Sutton	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	20	Percentage based on surficial geology; sandy soils
L V Sutton	10Bb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	80	Percentage based on surficial geology; sandy soils
Lansing	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	40	Percentage based on surficial geology, productive aquifers; loess = thin soils
Lansing	6Fb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	60	Percentage based on surficial geology, productive aquifers; coarse-grained soils
Laramie R Station	6Fb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	100	Based on aquifer and surficial geology coverages, Heath (1985)
Lawrence EC	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Alluvial valley with low coarse soils (<1% SNL)
Lee	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	30	Percentage based on surficial geology; sandy soils
Lee	10Bb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	70	Percentage based on surficial geology; sandy soils

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Leland Olds	7Eb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	50	Percentage based on surficial geology; assumed coarse soils
Leland Olds	7G	Thin Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	50	Percentage based on surficial geology; assumed coarse soils
Lon Wright	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	30	Alluvial based on predominant Heath, productive aquifer; percentage based on soil textures
Lon Wright	7Eb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	70	Alluvial based on predominant Heath, productive aquifer; percentage based on soil textures
Louisa	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	50	Alluvial Valley; significant coarse-grained deposits
Louisa	7Eb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	50	Alluvial Valley; significant coarse-grained deposits
Marion	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	100	Assigned to Glaciated Central region based on surficial geology (pre-Wisconsin drift)
Marshall	8D	Regolith	1	Metamorphic and Igneous	100	Based on surficial geology
Martin Lake	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Setting based on aquifer and surficial geology coverages
Mayo	8D	Regolith	1	Metamorphic and Igneous	100	Based on surficial geology
Meramec	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Based on surficial, predominant Heath
Merom	7D	Buried Valley	4	Sand and Gravel	100	Glaciofluvial aquifer overlaid by alluvial deposits
Miami Fort	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Assigned based on productive aquifers, surficial geology and soil (3% SNL)

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Milton R Young	7G	Thin Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	100	Based on principal aquifer and surficial geology coverages
Mitchell	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	60	Percentage based on surficial geology; thin regolith inferred from colluvium
Mitchell	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	40	Percentage based on surficial geology; soils 0 % SNL
Mitchell	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Setting based on surficial geology; low SNL (< 1%) = overbank deposits
Mohave	2Ha	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Setting based on predominant surficial geology, Heath (1985)
Monroe	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Based on Heath region, productive aquifers, soils
Morgantown	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Assigned based on location and aquifer and surficial geology coverages; Heath region incorrect (it's Atlantic Coastal Plain, not Piedmont)
Mountaineer (1301)	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Setting based on surficial geology; low SNL (10%) = overbank deposits
Mt Storm	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	100	Setting based on surficial geology, aquifer coverages; thin soils inferred from surficial geology
Muscatine Plant #1	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	50	Alluvial Valley; significant coarse-grained deposits
Muscatine Plant #1	7Eb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	50	Alluvial Valley; significant coarse-grained deposits
Muskogee	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Surficial geology indicates alluvium/colluvium; Heath (1985) indicates fine soils over sands and gravels

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Neal North	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Alluvial Valley setting
Neal South	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Alluvial Valley setting
Nebraska City	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Alluvial based on predominant Heath, productive aquifer, soil textures
New Castle	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	20	Percentage and setting based on Heath region & surficial geology; thin regolith inferred from colluvium
New Castle	7D	Buried Valley	4	Sand and Gravel	80	Percentage and setting based on Heath region & book
Newton	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	100	Based on soils, surficial geology, aquifer coverages
North Omaha	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Alluvial based on predominant Heath, productive aquifer; soil texture (28% SCL, 10% SNL) = overbank deposits
Northeastern	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	40	Percentage based on surficial geology, which indicates thin residual soils
Northeastern	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	60	Percentage based on surficial geology; soils < 2% SNL
Nucla	4B	Consolidated Sedimentary Rock	2	Bedded Sedimentary Rock	100	Based on surficial geology, aquifer coverages
Oklaunion	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	100	Setting based on surficial geology; thin soil inferred
Paradise	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Predominant alluvial setting (93% alluvium); soils have significant fines (SNL = 0%)
Petersburg	7D	Buried Valley	4	Sand and Gravel	100	Glaciofluvial aquifer in alluvial valley region (similar to 1043)

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Pleasant Prairie	7Ac	Glacial Till Over Solution Limestone	12	Solution Limestone	100	Setting based on aquifer and soil coverages (high SCL soils)
Port Washington	7Ac	Glacial Till Over Solution Limestone	12	Solution Limestone	100	Setting based on aquifer and soil coverages (high SCL soils)
Portland	7Ac	Glacial Till Over Solution Limestone	12	Solution Limestone	100	Setting based on aquifer and surficial geology coverage
Possum Point	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Based on productive aquifer coverage; Heath region incorrect
Potomac River	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	50	Percentage based on surficial geology coverage; Heath region incorrect
Potomac River	10Bb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	50	Percentage based on surficial geology coverage; sandy soils (51% SNL) = no overbank deposits; Heath region incorrect
Presque Isle	9F	Moraine	4	Sand and Gravel	100	Based on surficial geology, Heath region, soils
R Gallagher	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Predominant alluvial setting; soils have significant fines (SCL+SLT = 99%)
R M Schahfer	7D	Buried Valley	4	Sand and Gravel	100	Glaciofluvial aquifer in alluvial valley region
Reid Gardner	2C	Alluvial Fans	5	Alluvial Basins Valleys and Fans	100	Based on surficial geology; consistent with productive aquifers
Richard Gorsuch	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Assigned based on productive aquifers, surficial geology and soil (3% SNL)
Riverbend	8D	Regolith	1	Metamorphic and Igneous	100	Based on surficial geology
Rodemacher	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	50	Setting percentage determined from Heath, productive aquifer, and surficial geology coverages

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Rodemacher	10Ba	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	50	Setting percentage determined from Heath, productive aquifer, and surficial geology coverages
Roxboro	8D	Regolith	1	Metamorphic and Igneous	100	Based on surficial geology, productive aquifers
Sandow	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Setting based on aquifer and surficial geology coverages; Heath region coverage is incorrect (based on Heath [1985] and aquifer coverages)
Scherer	8D	Regolith	1	Metamorphic and Igneous	100	Most common Piedmont setting (residuum)
Shawnee	10Bb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	100	Predominant alluvial setting (100% alluvium); soils have low fines (SCL = 9%)
Shawville	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	100	Setting based on aquifer coverages & Heath (1985); thin regolith inferred from colluvium
Sheldon	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	30	Percentage based on productive aquifer coverage; buried valley indicated by Heath (1985)
Sheldon	7D	Buried Valley	4	Sand and Gravel	70	Percentage based on productive aquifer coverage; buried valley indicated by Heath (1985)
South Oak Creek	7Ac	Glacial Till Over Solution Limestone	12	Solution Limestone	100	Setting based on aquifer and soil coverages (high SCL soils)
Springerville	4B	Consolidated Sedimentary Rock	2	Bedded Sedimentary Rock	100	Assigned based on productive aquifers (consolidated sandstone)
St Johns River Power	11B	Coastal Deposits	4	Sand and Gravel	100	Based on sea island surficial geology
Stanton Energy Ctr	11A	Solution Limestone and Shallow Surficial Aquifers	12	Solution Limestone	100	Based on both aquifer coverages

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Stockton Cogen Company	2C	Alluvial Fans	5	Alluvial Basins Valleys and Fans	50	Percentage based on surficial geology; Central Valley soils show significant fines
Stockton Cogen Company	2Ha	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	50	Percentage based on surficial geology; Central Valley soils show significant fines
Syl Laskin	9E	Outwash	8	Outwash	60	Percentage based on surficial geology
Syl Laskin	9Ga	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	40	Percentage based on surficial geology
Tecumseh EC	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Alluvial valley with low coarse soils (<3% SNL)
Texas-New Mexico	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Based on productive aquifers, Heath (1985) (Heath region coverage is incorrect)
Titus	6Db	Alternating Sandstone, Limestone and Shale - Deep Regolith	2	Bedded Sedimentary Rock	100	Setting based on aquifer and surficial geology coverage; deep regolith inferred from red, massive clay
Trimble County	6E	Solution Limestone	12	Solution Limestone	40	Heath incorrect; Percentage based on surficial geology (56% alluvium, 44% clay); soils have significant fine-grained (1% SNL)
Trimble County	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	60	Heath incorrect; Percentage based on surficial geology (56% alluvium, 44% clay); soils have significant fine-grained (1% SNL)
Tyrone	6E	Solution Limestone	12	Solution Limestone	100	Based on principal aquifer coverage
Valley	7Ac	Glacial Till Over Solution Limestone	12	Solution Limestone	100	Setting based on aquifer and soil coverages (high SCL soils)
Vermilion	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	100	Based on aquifers, soils; soils don't suggest outwash like surficial geology does
Victor J Daniel Jr	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	60	Percentage based on surficial geology

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Victor J Daniel Jr	10Ba	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	40	Percentage based on surficial geology, soils
W A Parish	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	30	Percentage based on surficial geology and productive aquifer coverages
W A Parish	10Ba	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	70	Percentage based on surficial geology and productive aquifer coverages; high SCL (96%) = overbank deposits
W H Weatherspoon	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	30	Percentage based on surficial geology; sandy soils
W H Weatherspoon	10Bb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	70	Percentage based on surficial geology; sandy soils
W S Lee	8D	Regolith	1	Metamorphic and Igneous	100	Setting based on aquifers, surficial geology, soils, Heath (1985)
Wabash River	7D	Buried Valley	4	Sand and Gravel	100	Glaciofluvial aquifer in Alluvial Valley region
Walter C Beckjord	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	60	Percentage based on surficial geology; placed in glaciated central based on Heath (1985); soils 2% SNL
Walter C Beckjord	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	40	Percentage based on surficial geology; placed in glaciated central based on Heath (1985); soils 2% SNL
Wansley	8C	Mountain Flanks	2	Bedded Sedimentary Rock	30	Percentage based on surficial geology
Wansley	8E	River Alluvium	6	River Valleys and Floodplains with Overbank Deposit	70	Percentage based on surficial geology
Warrick	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Predominant alluvial setting; soils have significant fines (SCL+SLT = 94%)
Waukegan	7Bc	Outwash Over Solution Limestone	12	Solution Limestone	100	Based on soils, surficial geology, aquifer coverages

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Weston	9E	Outwash	8	Outwash	100	Setting based on productive aquifer, surficial geology coverages
Widows Creek	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	20	Percentage based on surficial geology; thin soils inferred from colluvium
Widows Creek	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	80	Percentage based on surficial geology; soils have significant fines (SCL+SLT > 25%)
Will County	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	40	Percentage based on surficial geology (65% Floodplain and alluvium gravel terraces)
Will County	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	60	Percentage based on surficial geology (65% Floodplain and alluvium gravel terraces)
Wyodak	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	100	Based on aquifer and surficial geology coverages, Heath (1985)
Yates	8D	Regolith	1	Metamorphic and Igneous	40	Percentage assigned based on surficial geology (59% alluvium/colluvium, 42% residuum)
Yates	8E	River Alluvium	6	River Valleys and Floodplains with Overbank Deposit	60	Percentage assigned based on surficial geology (59% alluvium/colluvium, 42% residuum)

SCL = silty clay loam; SNL = sandy loam; SLT = silt loam.

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Heath, R.C. 1985. *National Water Summary 1984*. *State Summaries of Groundwater Resources*. Water-Supply Paper 2275. U.S. Geological Survey, Washington, DC.

Attachment C-3: Climate Center Assignments

Plant	Climate Center	Explanation If Not Closest Climate Center
A B Brown	Indianapolis, IN	Closest Met Station (Nashville) receives much more precipitation (12.26” out of range) than the site location. Used second closest because only slightly below (1.3) expected precipitation range for plant.
A/C Power- Ace Operations	Las Vegas, NV	
Allen	Little Rock, AR	
Alma	Madison, WI	Closest Met Station (St. Cloud) receives less rain than plant location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant.
Antelope Valley	Bismarck, ND	
Arkwright	Watkinsville, GA	Closest Met Station (Atlanta) receives 6.96” more precipitation than plant location. Used second closest Met Station because 5-year averages are only slightly above (0.2) expected precipitation range for the plant.
Asheville	Knoxville, TN	
Baldwin	East St. Louis, IL	
Barry	Tallahassee, FL	Closest Met Station (New Orleans) receives much more precipitation (5.06” out of range) than the site location. Used second closest because only slightly above (3.4) expected precipitation range for plant.
Bay Front	Madison, WI	
Bay Shore	Put-in-Bay, OH	
Belews Creek	Greensboro, NC	
Ben French	Rapid City, SD	
Big Cajun 2	Lake Charles, LA	Closest Met Station (New Orleans) receives much more precipitation (5.06” out of range) than the site location. Used second closest because only slightly below (2.77) expected precipitation range for plant.
Big Sandy	Cincinnati, OH	Closest Met Station (Lexington) receives much more precipitation (8.35” out of range) than plant location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant.
Big Stone	St. Cloud, MN	

(continued)

Climate Center Assignments (continued)

Plant	Climate Center	Explanation If Not Closest Climate Center
Black Dog Steam Plant	Madison, WI	Closest Met Station (St Cloud) is dryer (<27.5”) than the 28-33” that the site receives. Madison fits in precipitation range (32.5”) and is second closest.
Blue Valley	Topeka, KS	
Bowen	Atlanta, GA	
Brandon Shores	Seabrook, NJ	
Buck	Greensboro, NC	
Bull Run	Knoxville, TN	
C D McIntosh Jr	Orlando, FL	Closest Met Station (Tampa) receives less precipitation (5.31” out of range) than site location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant.
C P Crane	Seabrook, NJ	
Cape Fear	Greensboro, NC	
Carbon	Salt Lake City, UT	
Cardinal	Pittsburgh, PA	
Cayuga	Indianapolis, IN	
Chalk Point	Seabrook, NJ	
Cholla	Phoenix, AZ	Closest Met Station (Flagstaff) receives much more precipitation (13.92” out of range) than plant location. Used second closest Met Station because 5-year averages were close (.31 higher) than the expected precipitation range for the plant.
Cliffside	Greensboro, NC	
Clover	Lynchburg, VA	
Coal Creek	Bismarck, ND	
Coleto Creek	San Antonio, TX	
Colstrip	Glasgow, MT	
Conemaugh	Pittsburgh, PA	
Conesville	Columbus, OH	
Council Bluffs	North Omaha, NE	
Crawford	East St. Louis, IL	
Crist	Tallahassee, FL	

(continued)

Climate Center Assignments (continued)

Plant	Climate Center	Explanation If Not Closest Climate Center
Cross	Charleston, SC	
Cumberland	Nashville, TN	
Dale	Lexington, KY	
Dallman	East St. Louis, IL	
Dan E Karn	East Lansing, MI	
Dan River	Greensboro, NC	
Danskammer	Bridgeport, CT	
Dave Johnston	Cheyenne, WY	
Dickerson	Seabrook, NJ	
Dolet Hills	Shreveport, LA	
Duck Creek	East St. Louis, IL	
Dunkirk	Ithaca, NY	
E D Edwards	Chicago, IL	
E W Brown	Lexington, KY	
Eckert Station	East Lansing, MI	
Edgewater	Madison, WI	
Elmer W Stout	Indianapolis, IN	
F B Culley	Indianapolis, IN	Closest Met Station (Nashville) receives much more precipitation (12.26” out of range) than plant location. Used second closest Met Station because 5-year & 30-year averages fell within expected precipitation range for the plant.
Fayette Power Prj	San Antonio, TX	
Flint Creek	Columbia, MO	Used http://www.weather.com and Envirofacts to determine that avg. precipitation for site was ~47”. The closest Met Station (Tulsa) receives much less (~17”) precipitation per year. Used second closest station.
Fort Martin	Pittsburgh, PA	
Frank E Ratts	Indianapolis, IN	
G G Allen	Greensboro, NC	
Gadsden	Atlanta, GA	

(continued)

Climate Center Assignments (continued)

Plant	Climate Center	Explanation If Not Closest Climate Center
Gallatin	Nashville, TN	
Gen J M Gavin	Cincinnati, OH	Closest Met Station (Columbus) receives less rain than plant location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant. Also average precipitation for the second closest Met Station was nearest to http://www.weather.com
Genoa	Madison, WI	
Gibson	Indianapolis, IN	
Gorgas	Atlanta, GA	
Green River	Indianapolis, IN	Closest Met Station (Nashville) receives much more precipitation (12.26” out of range) than plant location. Used third closest Met Station because 5-year averages fell within expected precipitation range for the plant.
Greene County	Atlanta, GA	
H B Robinson	Charleston, SC	
Hammond	Atlanta, GA	
Harllee Branch	Watkinsville, GA	
Harrison	Pittsburgh, PA	
Hatfield’s Ferry	Pittsburgh, PA	
Hennepin	Chicago, IL	
Heskett	Bismarck, ND	
Holcomb	Dodge City, KS	
Homer City	Pittsburgh, PA	
Hoot Lake	St. Cloud, MN	
Hugo	Shreveport, LA	Closest Met Station (Dallas) receives less precipitation (6.45” out of range) than plant location. Used second closest because only slightly above (2.07) expected precipitation range for plant.
Hunter	Grand Junction, CO	Closest Met Station (Salt Lake City) receives 8.6” more precipitation than plant location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant.
Huntington	Cedar City, UT	Two closest Met Stations are out of range. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant.
Intermountain	Ely, NV	Closest Met Station (Salt Lake City) receives 6.1” more precipitation than plant location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant.
J H Campbell	East Lansing, MI	

(continued)

Climate Center Assignments (continued)

Plant	Climate Center	Explanation If Not Closest Climate Center
J M Stuart	Cincinnati, OH	
J R Whiting	Put-in-Bay, OH	
Jack McDonough	Atlanta, GA	
Jack Watson	Tallahassee, FL	Closest Met Station (New Orleans) receives much more precipitation (5.06” out of range) than the site location. http://www.weather.com predicted average precipitation at plant location to be 65.2. Used third closest because its average was closest.
James H Miller Jr	Atlanta, GA	
Jim Bridger	Lander, WY	
John E Amos	Cincinnati, OH	The two closest Met Stations are out of the site’s precipitation range. Used third closest Met Station because 5-year averages fell within expected precipitation range for the plant. Also average precipitation for the second closest Met Station was nearest to http://www.weather.com average.
John Sevier	Knoxville, TN	
Johnsonville	Nashville, TN	
Joliet 29	Chicago, IL	
Keystone	Pittsburgh, PA	
Killen Station	Cincinnati, OH	
Kingston	Knoxville, TN	
Kraft	Charleston, SC	
L V Sutton	Charleston, SC	
Lansing	Madison, WI	
Laramie R Station	Cheyenne, WY	
Lawrence EC	Topeka, KS	
Lee	Greensboro, NC	
Leland Olds	Bismarck, ND	
Lon Wright	North Omaha, NE	
Louisa	Des Moines, IA	
Marion	East St. Louis, IL	
Marshall	Greensboro, NC	

(continued)

Climate Center Assignments (continued)

Plant	Climate Center	Explanation If Not Closest Climate Center
Martin Lake	Shreveport, LA	
Mayo	Lynchburg, VA	
Meramec	East St. Louis, IL	
Merom	Indianapolis, IN	
Miami Fort	Cincinnati, OH	
Milton R Young	Bismarck, ND	
Mitchell - PA	Pittsburgh, PA	
Mitchell - WV	Pittsburgh, PA	
Mohave	Las Vegas, NV	
Monroe	Put-in-Bay, OH	
Morgantown	Norfolk, VA	
Mountaineer (1301)	Cincinnati, OH	Closest Met Station (Columbus) receives more rain than plant location. Although second closest site also falls within range, used third closest Met Station because site geography was similar and the station's 5-year averages fell within expected precipitation range for the plant.
Mt Storm	Pittsburgh, PA	
Muscatine Plant #1	Des Moines, IA	
Muskogee	Tulsa, OK	
Neal North	North Omaha, NE	
Neal South	North Omaha, NE	
Nebraska City	North Omaha, NE	
New Castle	Pittsburgh, PA	
Newton	Indianapolis, IN	Closest Met Station (East St. Louis) receives less rain than plant location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant. Also average precipitation for the second closest Met Station was nearest to http://www.weather.com
North Omaha	North Omaha, NE	
Northeastern	Tulsa, OK	
Nucla	Grand Junction, CO	

(continued)

Climate Center Assignments (continued)

Plant	Climate Center	Explanation If Not Closest Climate Center
Oklaunion	Oklahoma City, OK	
Paradise	Cincinnati, OH	Closest Met Station (Nashville) receives much more precipitation (12.26” out of range) than plant location. Used third closest Met Station because 5-year averages fell within expected precipitation range for the plant.
Petersburg	Indianapolis, IN	
Pleasant Prairie	Chicago, IL	
Port Washington	Madison, WI	
Portland	Philadelphia, PA	
Possum Point	Norfolk, VA	
Potomac River	Seabrook, NJ	
Presque Isle	Sault Ste. Marie, MI	
R Gallagher	Cincinnati, OH	Closest Met Station (Lexington) receives much more precipitation (8.35” out of range) than plant location. Used second closest Met Station because 5-year & 30-year averages fell within expected precipitation range for the plant.
R M Schahfer	Chicago, IL	
Reid Gardner	Las Vegas, NV	
Richard Gorsuch	Columbus, OH	
Riverbend	Greensboro, NC	
Rodemacher	Lake Charles, LA	
Roxboro	Greensboro, NC	
Sandow	San Antonio, TX	
Scherer	Watkinsville, GA	Closest Met Station (Atlanta) receives 6.96” more precipitation than plant location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant.
Shawnee	East St. Louis, IL	
Shawville	Pittsburgh, PA	
Sheldon	North Omaha, NE	

(continued)

Climate Center Assignments (continued)

Plant	Climate Center	Explanation If Not Closest Climate Center
South Oak Creek	Chicago, IL	
Springerville	Albuquerque, NM	Closest Met Station (Flagstaff) receives much more precipitation (8.92” out of range) than plant location. Used second closest Met Station because 5-year averages were within the expected precipitation range for the plant.
St Johns River Power	Jacksonville, FL	
Stanton Energy Ctr	Orlando, FL	
Stockton Cogen Company	Sacramento, CA	
Syl Laskin	St. Cloud, MN	
Tecumseh EC	Topeka, KS	
Texas-New Mexico	San Antonio, TX	Closest Met Station (Dallas) received less precipitation than site location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant. Also average precipitation for the second closest Met Station was nearest to http://www.weather.com
Titus	Philadelphia, PA	
Trimble County	Cincinnati, OH	
Tyrone	Lexington, KY	
Valley	Madison, WI	
Vermilion	Chicago, IL	Closest Met Station (Indianapolis) receives more precipitation than plant location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant.
Victor J Daniel Jr	Tallahassee, FL	Closest Met Station (New Orleans) receives much more precipitation (5.06” out of range) than the site location. Used second closest because only slightly above (3.4) expected precipitation range for plant.
W A Parish	Shreveport, LA	2 Closest Met Stations (Lake Charles & San Antonio) are more than 4” out of range. Used third closest because only slightly above (1.65”) expected precipitation range for plant.
W H Weatherspoon	Greensboro, NC	
W S Lee	Watkinsville, GA	
Wabash River	Indianapolis, IN	
Walter C Beckjord	Cincinnati, OH	
Wansley	Atlanta, GA	
Warrick	Indianapolis, IN	Closest Met Station (Nashville) receives 12.2” more precipitation than plant location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant.

(continued)

Climate Center Assignments (continued)

Plant	Climate Center	Explanation If Not Closest Climate Center
Waukegan	Chicago, IL	
Weston	Madison, WI	
Widows Creek	Nashville, TN	
Will County	East St. Louis, IL	
Wyodak	Rapid City, SD	
Yates	Atlanta, GA	

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Attachment C-4: Waterbody Assignments and Flow

Plant	CUSEG	Nearest Reach	Reach Type	QLOW	QMEAN
A B Brown	05140202014	OHIO R	Regular Reach	9167.38965	150031.6875
A/C Power- Ace Operations	18090205005	SEARLES L	Lake Shoreline		
Allen	08010211007	HORN LAKE CUTOFF	Lake Shoreline		
Alma	07040003009	MISSISSIPPI R	Regular Reach	5683.02002	25397.4707
Antelope Valley	10130201005	ANTELOPE CR	Start Reach	0	96.87
Arkwright	03070103007	OCMULGEE R	Regular Reach	428.79999	2708.53003
Asheville	06010105026	FRENCH BROAD R	Regular Reach	412.04999	1722.34998
Baldwin	07140204004	KASKASKIA R	Regular Reach	351.72	3832.12012
Barry	03160204014	MOBILE R	Regular Reach	7561.14014	63275.23828
Bay Front	07070005036	L SUPERIOR	Great Lakes Shoreline		
Bay Shore	04100010003	L ERIE, U.S. SHORE	Great Lakes Shoreline	0	0
Belews Creek	03010103098	BELEWS L	Lake Shoreline		
Ben French	10120110010	CASTLE CR	Start Reach	2.96	18.62
Big Cajun 2	08070100005	MISSISSIPPI R	Regular Reach	100937.8125	466865.5625
Big Sandy	05070204008	BIG SANDY R	Regular Reach	152.02	5746.95996
Big Stone	07020001033	BIG STONE LAKE	Lake Shoreline		
Black Dog Steam Plant	07020012001	BLACK DOG LAKE	Lake Shoreline		
Blue Valley	10300101034	LITTLE BLUE R	Regular Reach	23.2	141.75
Bowen	03150104008	ETOWAH R	Regular Reach	413.13	2294.86011
Brandon Shores	02060003037	CURTIS BAY	Coastal Shoreline	0	0
Buck	03040103040	YADKIN R	Regular Reach	912.72998	4722.54004
Bull Run	06010207015	CLINCH R	Regular Reach	102.46	4732.3501
C D McIntosh Jr	03100205014	NO LAKE PARKER	Lake Shoreline		

(continued)

Waterbody Assignments and Flow (continued)

Plant	CUSEG	Nearest Reach	Reach Type	QLOW	QMEAN
C P Crane	02060003025	CURTIS BAY	Coastal Shoreline	0	0
Cape Fear	03030002001	HAW R	Regular Reach	58.98	1584.83997
Carbon	14060007018	PRICE R	Regular Reach	1.92	77
Cardinal	05030106033	OHIO R	Regular Reach	3391.62012	37533.17188
Cayuga	05120108001	WABASH R	Regular Reach	965.09003	10100.21973
Chalk Point	02060006009	PATUXENT R	Wide-River Shoreline	0	0
Cholla	15020008017	CHOLLA COOLING POND	Lake Shoreline		
Cliffside	03050105031	BROAD R	Regular Reach	332.17001	1510.08997
Clover	03010102027	ROANOKE R	Regular Reach	408.64001	2702.59009
Coal Creek	10130101018	UNKNOWN LAKE	Lake Shoreline		
Coleto Creek	12100303014	MARCELINAS CR	Start Reach	1.11	3.79
Colstrip	10100001108	ARMELLS CR, E FK	Start Reach	0	18.64
Conemaugh	05010007002	CONEMAUGH R	Regular Reach	194.53999	1553.52002
Conesville	05040004071	MUSKINGUM R	Regular Reach	447.98001	4707.08008
Council Bluffs	10230006004	MISSOURI R	Regular Reach	4402.58984	31444.83008
Crawford	07130011018	ILLINOIS R	Regular Reach	3444.66992	20788.71094
Crist	03140305001	ESCAMBIA R	Terminal Reach	845.46002	6772.5498
Cross	03050201022	DIVERS CANAL TO LAKE MOU	Lake Shoreline		
Cumberland	05130205017	CUMBERLAND R	Regular Reach	536.47998	25322.66016
Dale	05100205047	KENTUCKY R	Regular Reach	35.32	5213.06982
Dallman	07130007003	LAKE SPRINGFIELD	Lake Shoreline		
Dan E Karn	04080103005	L HURON U.S. SH SAGINAW BAY	Great Lakes Shoreline	0	0
Dan River	03010103014	DAN R	Regular Reach	358.12	1954.15002
Danskammer	02020008022	HUDSON R	Wide-River Shoreline	0	0
Dave Johnston	10180007005	N PLATTE R	Regular Reach	65.24	502.87
Dickerson	02070008013	POTOMAC R	Regular Reach	895.57001	10528.36035
Dolet Hills	11140206019	BAYOU PIERRE LAKE	Lake Shoreline		

(continued)

Waterbody Assignments and Flow (continued)

Plant	CUSEG	Nearest Reach	Reach Type	QLOW	QMEAN
Duck Creek	07130003010	L CHAUTAUQUA	Lake Shoreline		
Dunkirk	04120101003	L ERIE, U.S. SHORE	Great Lakes Shoreline	0	0
E D Edwards	07130003018	ILLINOIS R	Regular Reach	2998.32007	13899.62988
E W Brown	05100205015	HERRINGTON LAKE	Lake Shoreline		
Eckert Station	04050004003	GRAND R	Regular Reach	73.47	484.28
Edgewater	04030101002	L MICHIGAN	Great Lakes Shoreline	0	0
Elmer W Stout	05120201005	WHITE R	Regular Reach	70.17	1429.92004
F B Culley	05140201001	OHIO R	Regular Reach	8728.7002	131543.0625
Fayette Power Prj	12090301003	CEDAR CREEK RESERVOIR	Lake Shoreline		
Flint Creek	11110103031	SWEPCO RSRVR,LT FLINT CK	Lake Shoreline		
Fort Martin	05020003001	MONONGAHELA R	Regular Reach	293.66	4497.75
Frank E Ratts	05120202003	WHITE R	Regular Reach	343.59	11525.13965
G G Allen	03050101009	CATAWBA R	Regular Reach	462.92001	2958.09009
Gadsden	03150106041	COOSA R	Regular Reach	1096.10999	9468
Gallatin	05130201006	OLD HICKORY L	Lake Shoreline		
Gen J M Gavin	05030202005	OHIO R	Regular Reach	4258.12012	55143.35938
Genoa	07060001017	MISSISSIPPI R	Regular Reach	6434.18018	29379.25
Gibson	05120113013	WABASH R	Regular Reach	2247.6001	26799.73047
Gorgas	03160109002	BLACK WARRIOR R, MULBERRY F	Lake Shoreline		
Green River	05110003001	GREEN R	Regular Reach	320.06	9752
Greene County	03160113011	BLACK WARRIOR R	Regular Reach	304.73001	9820.04004
H B Robinson	03040201042	L ROBERTSON	Lake Shoreline		
Hammond	03150105025	COOSA R	Regular Reach	1196.82996	6569.95996
Harllee Branch	03070101006	L SINCLAIR	Lake Shoreline		
Harrison	05020002008	WEST FORK R	Regular Reach	33.03	1038.32996
Hatfield's Ferry	05020005026	MONONGAHELA R	Regular Reach	479.79999	8278.94043
Hennepin	07130001026	ILLINOIS R	Regular Reach	3233.23999	13146.83984
Heskett	10130101001	MISSOURI R	Regular Reach	3461.55005	22744.26953

(continued)

Waterbody Assignments and Flow (continued)

Plant	CUSEG	Nearest Reach	Reach Type	QLOW	QMEAN
Holcomb	11030001001	ARKANSAS R	Regular Reach	0	197.92999
Homer City	05010007015	TWO LICK CR	Regular Reach	4.53	295.22
Hoot Lake	09020103002	OTTER TAIL R	Regular Reach	12.45	271.35999
Hugo	11140105041	KIAMICHI CR, N FK	Start Reach	2.55	53.16
Hunter	14060009034	ROCK CANYON CR	Start Reach	0	0.1
Huntington	14060009020	HUNTINGTON CR	Regular Reach	10.75	91.1
Intermountain		none		0	0
J H Campbell	04050002001	L MICHIGAN	Great Lakes Shoreline	0	0
J M Stuart	05090201024	OHIO R	Regular Reach	6767.47021	92214.6875
J R Whiting	04100001002	L ERIE, U.S. SHORE	Great Lakes Shoreline	0	0
Jack McDonough	03130002044	CHATTAHOOCHEE R	Regular Reach	726.45001	2952.18994
Jack Watson	03170009034	BILOXI BAY	Coastal Shoreline	0	0
James H Miller Jr	03160111005	BLACK WARRIOR R, LOCUST FK	Lake Shoreline		
Jim Bridger	14040105011	UNKNOWN LAKE	Lake Shoreline		
John E Amos	05050008007	KANAWHA R	Regular Reach	1390.22998	14930.83984
John Sevier	06010104011	HOLSTON R	Regular Reach	633	4079.15991
Johnsonville	06040005007	KENTUCKY L	Lake Shoreline		
Joliet 29	07120004004	DES PLAINS R	Regular Reach	1029.93005	3809.69995
Keystone	05010006002	CROOKED CR	Regular Reach	30.72	422.14999
Killen Station	05090201024	OHIO R	Regular Reach	6767.47021	92214.6875
Kingston	06010207001	CLINCH R	Regular Reach	266.35999	7347.89014
Kraft	03060109007	SAVANNAH R	Regular Reach	3570.52002	12365
L V Sutton	03030005011	CAPE FEAR R	Regular Reach	619.95001	8594.57031
Lansing	07060001009	MISSISSIPPI R	Regular Reach	7684.02002	32253.15039
Laramie R Station	10180011002	LARAMIE R	Regular Reach	28.53	90.8
Lawrence EC	10270104021	KANSAS R	Regular Reach	403.81	6720.29004
Lee	03020201007	NEUSE R	Regular Reach	76.18	1657.39001
Leland Olds	10130101020	MISSOURI R	Regular Reach	4270.4502	21650.67969

(continued)

Waterbody Assignments and Flow (continued)

Plant	CUSEG	Nearest Reach	Reach Type	QLOW	QMEAN
Lon Wright	10220003048	RAWHIDE CR	Start Reach	0.94	11.59
Louisa	07080101003	MISSISSIPPI R	Regular Reach	15067.92969	54665.96094
Marion	05140204030	L OF EGYPT	Lake Shoreline		
Marshall	03050101015	L NORMAN	Lake Shoreline		
Martin Lake	12010002050	MARTIN LAKE	Lake Shoreline		
Mayo	03010104045	MAYO CR	Start Reach	5.99	61.03
Meramec	07140101014	MISSISSIPPI R	Regular Reach	33305	177021.1875
Merom	05120111011	TURTLE CR RESERVOIR	Lake Shoreline		
Miami Fort	05090203012	OHIO R	Regular Reach	6516.18994	98615.0625
Milton R Young	10130101024	NELSON LAKE AND MISSOURI RIVER	Lake Shoreline		
Mitchell - PA	05020005002	MONONGAHELA R	Regular Reach	848.58002	9284.13965
Mitchell - WV	05030106013	OHIO R	Regular Reach	3419.20996	38713.19922
Mohave	15030101011	COLORADO R	Regular Reach	1916.72998	12134.36035
Monroe	04100001002	L ERIE, U.S. SHORE	Great Lakes Shoreline	0	0
Morgantown	02070011051	POTOMAC R	Wide-River Shoreline	0	0
Mountaineer (1301)	05030202008	OHIO R	Regular Reach	4242.58984	54823.21094
Mt Storm	02070002027	STONY R RES	Lake Shoreline		
Muscatine Plant #1	07080101005	MISSISSIPPI R	Regular Reach	14573.71973	54469.48047
Muskogee	11110102012	ARKANSAS R	Regular Reach	227.57001	21258.39062
Neal North	10230001021	MISSOURI R	Regular Reach	4217.7998	29486.82031
Neal South	10230001021	MISSOURI R	Regular Reach	4217.7998	29486.82031
Nebraska City	10240001002	MISSOURI R	Regular Reach	5807.77002	36764.01172
New Castle	05030104002	BEAVER R	Regular Reach	268.48001	2425.32007
Newton	05120114006	NEWTON LAKE	Lake Shoreline		
North Omaha	10230006009	MISSOURI R	Regular Reach	4365.6499	31400.93945
Northeastern	11070105012	VERDIGRIS R	Regular Reach	3.85	2168.47998
Nucla	14030003012	SAN MIGUEL R	Regular Reach	8.1	307.64001
Oklaunion	11130302061	BOGGY CR	Start Reach	0.09	14.93

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Waterbody Assignments and Flow (continued)

Plant	CUSEG	Nearest Reach	Reach Type	QLOW	QMEAN
Paradise	05110003003	GREEN R	Regular Reach	316.59	9663.71973
Petersburg	05120202003	WHITE R	Regular Reach	343.59	11525.13965
Pleasant Prairie	07120004012	L MICHIGAN AND J	Lake Shoreline		
Port Washington	04030101002	L MICHIGAN	Great Lakes Shoreline	0	0
Portland	02040105012	DELAWARE R	Regular Reach	1995.12	9089.00977
Possum Point	02070011074	POTOMAC R	Wide-River Shoreline	0	0
Potomac River	02070010025	POTOMAC R	Artificial Open Water Reach	919.89001	11721.87988
Presque Isle	04020105002	L SUPERIOR, U.S. SHORE	Great Lakes Shoreline	0	0
R Gallagher	05140101001	OHIO R	Regular Reach	7634.39014	119152.1875
R M Schahfer	07120001012	KANAKEE R	Regular Reach	458.92001	1410.56006
Reid Gardner	15010012006	MUDDY R	Regular Reach	0.68	19.22
Richard Gorsuch	05030202039	OHIO R	Regular Reach	4079.81006	48956.14062
Riverbend	03050101012	CATAWBA R	Regular Reach	412.28	2623.09009
Rodemacher	11140207020	RODEMACHER LAKE	Lake Shoreline		
Roxboro	03010104034	HYCO L	Lake Shoreline		
Sandow	12070102012	ALCOA LAKE	Lake Shoreline		
Scherer	03070103012	OCMULGEE R	Start Reach	655.48999	2490.72998
Shawnee	05140206009	OHIO R	Regular Reach	21748.59961	288452.1875
Shawville	02050201002	SUSQUEHANNA R, W BR	Regular Reach	96.9	1947.33997
Sheldon	10240008030	UNKNOWN LAKE	Lake Shoreline		
South Oak Creek	04040002004	L MICHIGAN	Great Lakes Shoreline	0	0
Springerville	15020002025	*A	Start Reach	0	2.49
St Johns River Power	03080103003	ST JOHNS R	Wide-River Shoreline	0	0
Stanton Energy Ctr	03080101036	ECOHLOCKHATCHEE R	Start Reach	5.95	131.42999
Stockton Cogen Company	18040002005	LITTLEJOHNS CR	Start Reach	0.21	50.61
Syl Laskin	04010201034	COLBY L AND PARTRIDGE R	Lake Shoreline		
Tecumseh EC	10270102003	KANSAS R	Regular Reach	388.51999	5923.74023
Texas-New Mexico	12070101008	LITTLE BRAZOS R	Start Reach	0.55	139.05

(continued)

Waterbody Assignments and Flow (continued)

Plant	CUSEG	Nearest Reach	Reach Type	QLOW	QMEAN
Titus	02040203010	SCHUYLKILL R	Regular Reach	91.25	1880.77002
Trimble County	05140101007	OHIO R	Regular Reach	7524.29004	117896.3125
Tyrone	05100205013	KENTUCKY R	Regular Reach	154.36	7097.54004
Valley	04040003001	MILWAUKEE R	Terminal Reach	10.71	540.60999
Vermilion	05120109006	VERMILION R, M FK	Regular Reach	3.45	340.35999
Victor J Daniel Jr	03170006007	PASCAGOULA R	Regular Reach	1256.55005	12878.25
W A Parish	12070104021	SMITHERS L	Lake Shoreline		
W H Weatherspoon	03040203016	LUMBER R	Regular Reach	97.9	865.13
W S Lee	03050109066	SALADA R	Regular Reach	20.68	461.51001
Wabash River	05120111018	WABASH R	Regular Reach	985.53998	10551.67969
Walter C Beckjord	05090201001	OHIO R	Regular Reach	6416.77002	92084.0625
Wansley	03130002032	CHATTAHOOCHEE R	Regular Reach	702.71002	4400.72021
Warrick	05140201022	LITTLE PIGEON CR	Regular Reach	61.57	1149.60999
Waukegan	04040002002	L MICHIGAN	Great Lakes Shoreline	0	0
Weston	07070002023	WISCONSIN R	Regular Reach	1069.30005	3484.32007
Widows Creek	06030001049	TENNESSEE R	Regular Reach	7221.95996	38237.07031
Will County	07110009002	WOOD R	Start Reach	29	87.81
Wyodak	10120201038	DONKEY CR	Start Reach	0	4.4
Yates	03130002061	CHATTAHOOCHEE R	Regular Reach	702.21997	4063.29004

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Appendix D. MINTEQA2 Nonlinear Sorption Isotherms

D.1 Overview of MINTEQA2 Modeling

Chemicals in leachate can be subject to complex geochemical interactions in soil and groundwater, which can strongly affect their rate of transport in the subsurface. EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP) treats these interactions as equilibrium sorption processes. The equilibrium assumption means that the sorption process occurs instantaneously, or at least very quickly relative to the time scale of constituent transport. Although sorption—or the attachment of leachate constituents to solid soil or aquifer particles—may result from multiple chemical processes, EPACMTP lumps these processes together into an effective soil-water partition coefficient (K_d). The retardation factor (R) accounts for the effects of equilibrium sorption of dissolved constituents onto the solid phase, removing them from solution and reducing the available mass in the dissolved phase. R, a function of the constituent-specific K_d and the soil or aquifer properties, is calculated as:

$$R = 1 + \frac{\rho_b \times K_d}{\Phi} \qquad \text{(D-1)}$$

where

R = Retardation factor
ρ_b = Soil or aquifer bulk density (g/cm^3)
K_d = Solid-water partition coefficient (g/cm^3)
ϕ = Water content (in unsaturated zone) or porosity (in saturated zone).

An isotherm is an expression of the equilibrium relationship between the aqueous concentration and the sorbed concentration of a metal (or other constituent) at a constant temperature. For metals, EPACMTP accounts for more complex geochemical reactions by using effective sorption isotherms generated using EPA's geochemical equilibrium speciation model for dilute aqueous systems, MINTEQA2 (U.S. EPA, 1991).

The MINTEQA2 model was used to generate one set of isotherms for each metal reflecting the range in geochemical environments expected at waste sites across the nation. The variability in geochemical environments at CCW sites across the country was represented by five geochemical master variables (groundwater composition, pH, concentration of iron oxide adsorption sites, leachate ionic strength, and concentration of dissolved and particulate natural organic matter), and the MINTEQA2 modeling was repeated (separately for each metal) for numerous combinations of master variable settings. This procedure resulted in nonlinear K_d versus aqueous metal concentration curves for combinations of master variable settings spanning the range of reasonable values (U.S. EPA 2003a).

For each metal, the resulting set of isotherms was tabulated into a supplementary input data file for use by the EPACMTP model, hereafter referred to as an "empirical nonlinear isotherm." In the fate and transport modeling for a particular metal, EPACMTP was executed, and the national probability distributions for these five master variables formed the basis for the Monte Carlo selection of the appropriate adsorption isotherm.

In modeling metals transport in the unsaturated zone, EPACMTP uses a range of K_d values from the nonlinear sorption isotherms. However, in modeling metals transport in the saturated zone, EPACMTP selects the lowest from all available K_d values corresponding to concentrations less than or equal to the maximum water table concentration. For more details see the *EPACMTP Technical Background Document* (U.S. EPA, 2003b). This simplification in the saturated zone is required for all solution options and is based on the assumption that, after dilution of the leachate plume in groundwater, the concentrations of metals will typically be in a range where the isotherm is approximately linear. However, this assumption may not be valid when the metal concentrations in the leachate are exceedingly high. Although EPACMTP is able to account for the effect of the geochemical environment at a site on the mobility of metals, the model assumes that the geochemical environment at a site is constant and not affected by the presence of the leachate plume. In reality, the presence of a leachate plume may alter the ambient geochemical environment.

D.2 Previous CCW Metals Modeling Effort

In a previous risk assessment for fossil fuel combustion wastes (FFCWs) conducted in 1998 (U.S. EPA, 1998), sorption isotherms generated using MINTEQA2 were used in EPACMTP to account for metal partitioning. However, these isotherms were not calculated specifically for use in FFCW modeling—they had been computed using MINTEQA2 in 1995 for use in modeling support for the Hazardous Waste Identification Rule (HWIR).

The disposal scenario for HWIR was the industrial Resource Conservation and Recovery Act (RCRA) Subtitle D nonhazardous waste landfill. In fact, the MINTEQA2 modeling that produced the isotherms had originally been designed to represent municipal solid waste landfills, and leachate from those landfills had been sampled so that appropriate forms of leachate organic acids at various concentrations could be included in the modeling. For the HWIR analysis, the scenario was changed to industrial Subtitle D, and only the isotherms corresponding to low concentrations of the leachate organic acids were used for HWIR modeling. The same isotherms were used in the 1998 FFCW risk assessment. As in the HWIR modeling, only the isotherms corresponding to the lowest setting of leachate organic carbon were used.

In 1999, EPA received review comments concerning the use of the industrial Subtitle D metal partitioning isotherms in the 1998 risk assessment. The most comprehensive review was prepared by Charles Norris and Christina Hubbard on behalf of the Environmental Defense Fund and other environmental advocacy groups (Norris and Hubbard, 1999). The Norris and Hubbard report criticized the 1998 risk assessment for using MINTEQA2 isotherms designed for a different scenario (nonhazardous industrial landfills). Norris and Hubbard also offered 20 specific criticisms on the input parameters and other factors involved in the MINTEQA2 modeling. EPA responded by evaluating each of these criticisms through review and assessment of MINTEQA2 input values, model sensitivity tests, and consultations with experts. This review

is documented in U.S. EPA (2000, 2001a). The evaluation of the Norris and Hubbard comments resulted in suggested revisions in the MINTEQA2 modeling strategy, as described in U.S. EPA (2001b).

Based on a review of available information on CCW leachate composition and an analysis of the potential effects of this composition on metals mobility, EPA (U.S. EPA, 2001b) also determined that if MINTEQA2 is to be used at CCW sites, leachate from CCW facilities should be studied to look for trends in composition, especially with regard to the concentrations of constituents that may

- Contribute to elevated groundwater pH
- Compete with the contaminant metal for sorption sites and thus result in reduced metal sorption (e.g., Ca, Mg, SO_4, other metals)
- Complex with the contaminant metal so that the metal is less likely to be sorbed (e.g., SO_4, CO_3, organic ligands)
- Precipitate with the contaminant metal (e.g., SO_4, CO_3).

D.3 MINTEQA2 Modeling Revisions for CCW Risk Assessment

Many of the suggested revisions from U.S. EPA (2001b) were implemented in the MINTEQA2 modeling for the current CCW risk assessment. Some of the suggested revisions were not implemented, either because they were not applicable (e.g., organic carbon assumptions were not changed, because CCW leachate has negligible organic carbon) or because models or data were not adequate to carry forth the recommendation. These revisions are discussed in greater detail in U.S. EPA (2003c).

In addition to revising the MINTEQA2 model, EPA compiled leachate characteristics into the CCW constituent database (see **Appendix A**) and statistically analyzed these data to identify three chemically distinct CCW leachate types: conventional CCW (including ash and flue gas desulfurization [FGD] sludge), codisposed CCW and coal cleaning wastes, and fluidized bed combustion (FBC) waste. Leachate concentration ranges for major ions (e.g., Ca, SO_4, Mg, Na, Cl, etc.) and pH were developed for each of these waste types and were used to represent CCW leachate during MINTEQA2 modeling.

As needed, sorption reactions were included for those CCW constituents known to undergo significant sorption. Including elevated concentrations of leachate constituents and their corresponding sorption reactions in the MINTEQA2 model allowed for full competition with the contaminant metal for sorption sites. The metal solubilizing effect through complexation between the contaminant metal and dissolved ligands was also included, as was the potential for metal precipitation. Because precipitation of the metal can serve to attenuate the transportable concentration, the equilibrium fraction in all three phases (dissolved, sorbed, and precipitated) were stored and made available for use by EPACMTP. The precipitated fraction was used to develop a solubility limit that was used during EPACMTP modeling (U.S. EPA, 2003c).

D.4 MINTEQA2 Modeling for CCW Risk Assessment

The expected natural variability in K_d for a particular metal was represented during the MINTEQA2 modeling effort by varying the input parameters that most impact K_d: groundwater type (carbonate or noncarbonate), pH, concentration of aquifer sorbents, composition and concentration level of CCW leachate, and concentration of the contaminant metal. The natural pH range for the two groundwater types was sampled from a range of 7 to 8 for carbonate aquifers and 4 to 10 for noncarbonate aquifers (U.S. EPA, 2003c).

In addition, CCW leachate ranges from acidic (pH < 2) to highly alkaline (pH > 12), and it can impact unsaturated zone and groundwater pH. To account for this possibility, the CCW leachate/ groundwater system was equilibrated at a series of pH values that spanned the range of expected variability in mixed CCW leachate-groundwater systems (U.S. EPA, 2003c).

To account for the variability in the sorption capacity of soil and aquifer materials, the soil and groundwater systems were equilibrated with various concentrations of two commonly occurring natural sorbents: ferric (iron) oxyhydroxide (FeOx) and particulate organic matter (POM). CCW leachate can include elevated concentrations of inorganic constituents such as calcium, sulfate, sodium, potassium, and chloride, which may reduce sorption of metals due to competition for sorption sites or complexation with metals in solution. To account for this effect, these leachate components were added to the MINTEQA2 model inputs at concentrations representative of the three CCW waste types (conventional CCWs, codisposed CCW and coal cleaning wastes, and FBC wastes). This new MINTEQA2 master variable is termed leachate "richness" or ionic strength (U.S. EPA, 2003c).

The results of each MINTEQA2 model run were compiled as the equilibrium distribution of the contaminant metal among dissolved, sorbed, and precipitated fractions for each metal concentration, and were saved in a separate file indexed with the settings of all variables used to define the system. These files were produced for all possible values for the variables defining the system, and were compiled into a database of indexed K_d values for use in the EPACMTP fate and transport model (U.S. EPA, 2003c).

D.5 EPACMTP Modeling Revisions to Accommodate MINTEQA2 Updates

EPA updated EPACMTP to support the new system variable (leachate ionic strength) for isotherm selection, to address issues regarding the impacts of leachate pH on ambient soil and aquifer pH, and to address issues regarding solubility limits for metals in solution. A brief description of these model changes are discussed below, with more detail provided in U.S. EPA (2003d).

Ionic Strength. A new system or "master" variable was added to include ionic strength as a key for choosing the representative isotherm from the database for both the unsaturated and saturated zones.

Leachate Effects on Geochemical Environment. These effects were addressed in EPACMTP under the following constraints: (1) no significant impairment of the computational efficiency for probabilistic applications; (2) data requirements limited to readily available data;

and (3) a scientifically defensible approach, given significant uncertainties with respect to the true impacts of leachate pH on the subsurface. Two modifications to the EPACMTP were considered: (1) determine the governing pH in the soil column (either the pH of the leachate or the native soils); and (2) determine the pH of the saturated zone as a result of the infiltrating leachate.

The approach selected for determining the governing pH of the soil column (unsaturated zone) beneath the waste management unit (WMU) compares the operational life of the WMU (the duration of leaching) to an estimate of the first arrival time of the contaminant front at the water table (a surrogate for the residence time of the contaminant in the soil column). If the operational life of the WMU is *relatively* long compared to the time required for the contaminant to migrate to the water table, there is a high likelihood that the leachate permeates the soil column and that the pH environment is governed by the leachate. Conversely, a relatively short operational life and retarded contaminant migration would favor ambient soil pH conditions. An analysis of the relationship between operational life and travel time indicated that a ratio of approximately 5 (operational life over travel time) would, in many cases, result in a balanced selection of cases where leachate pH governs versus cases where soil pH governs over approximately 10,000 Monte Carlo iterations.

For each iteration of EPACMTP, the operational life was compared to a travel-time estimate based on a K_d averaged from isotherms selected based on the leachate pH and soil pH. If the ratio was greater than 5, the pH of the leachate was assumed to govern, and the pH of the leachate was used to select the isotherm for transport in the unsaturated zone. If the ratio was less than 5, the soil pH was used to select the isotherm.

In the saturated zone, the impacts of leachate pH were handled using a simple homogeneous mixing calculation. The volume of leachate released from the WMU was mixed with the volume of the aquifer that was likely to be impacted by a plume. The resulting mixed pH was used to select the isotherm for transport in the saturated zone with one limitation: in carbonate environments, the mixed pH in the aquifer was not allowed to drop below a pH of 6. Such acid conditions would likely result in significant dissolution of the soil matrix.

Metal Solubility Limits. As mentioned above, each sorption isotherm comprises equilibrium concentrations of the three contaminant phases (dissolved, sorbed, and precipitated) over a range of total concentration values. An examination of the change in the dissolved-phase concentrations relative to changes in the total concentration in any isotherm reveals solubility behavior for that contaminant: if the dissolved component does not change with increasing total concentration, a solubility limit has been achieved. If, however, the dissolved component increases along with the total concentration, then there is capacity for more dissolved mass in the groundwater or soil porewater.

EPACMTP uses this information (contained in each isotherm file) to determine if a solubility limit should be imposed in the saturated zone. Once an isotherm has been selected (after pH considerations have been addressed), the equilibrium states corresponding to the three highest total concentrations are examined. If the dissolved concentration changes more than one tenth of one percent over the last three points, then EPACMTP assumes there is no solubility limit. If the change in dissolved concentration is less than one tenth of one percent, EPACMTP

assumes a solubility limit has been reached and caps the concentration of the leachate entering the saturated zone at the water table to that limit.

D.6 Sampled K_ds from MINTEQA2 Isotherms by EPACMTP

As described above, a range of K_ds from an isotherm were used by EPACMTP in each unsaturated zone transport simulation. To simplify the presentation of K_d here, an *effective* K_d value was calculated and reported by EPACMTP. An effective K_d was determined by first estimating the value of the retardation factor, described in Equation D-1, as follows:

$$R = \frac{t_{WT} \times q}{d_{soil}}$$

where

t_{wt} = time for leachate to reach the water table (yr)
q = seepage velocity of leachate through the unsaturated soil column (m/yr)
d_{dsoil} = depth to the water table or length of the unsaturated soil column (m)

Substituting this value for R in Equation D-1 and solving for K_d yields an effective K_d that is based on the first arrival of the leachate front at the water table.

Table D-1 presents selected percentiles of K_d sampled from the MINTEQA2 isotherms for every waste management modeling scenario conducted in the CCW risk assessment for the groundwater pathway. Each scenario corresponds to a unique combination of waste type, metal species, waste management unit type, and subsurface domain (unsaturated zone or saturated zone). The values presented for the saturated zone are taken from the set of actual K_d values used in each modeling scenario.

Table D-1. Select Percentiles of K_d Sampled from MINTEQA2 Isotherms by Updated EPACMTP by Waste Type, Metal Species, WMU Type, and Subsurface Domain

Waste Stream	Metal	CASID	WMU	Zone	Percentiles of K_d							
					10%	25%	50%	75%	80%	85%	90%	95%
Ash	Aluminum	7429905	LF	Saturated	8.5E-20	3.0E-16	5.1E-10	5.0E-03	7.1E-02	9.2E-01	1.6E+00	2.8E+00
Ash	Aluminum	7429905	SI	Saturated	8.6E-20	2.5E-10	2.6E-04	9.4E-01	2.2E+00	2.7E+00	2.8E+00	6.2E+00
Ash	Aluminum	7429905	LF	Unsaturated	6.9E-03	1.0E-01	2.0E-01	1.8E+01	5.9E+01	1.0E+02	1.8E+02	3.7E+02
Ash	Aluminum	7429905	SI	Unsaturated	2.0E-11	3.7E-02	1.6E-01	1.1E+00	1.6E+00	2.8E+00	3.0E+00	6.6E+00
Ash	Antimony	7440360	LF	Saturated	4.3E-03	2.5E-02	7.5E-02	2.0E-01	2.1E-01	3.0E-01	3.4E-01	7.1E-01
Ash	Antimony	7440360	SI	Saturated	2.8E-03	1.9E-02	9.6E-02	2.0E-01	2.1E-01	3.3E-01	3.5E-01	5.9E-01
Ash	Antimony	7440360	LF	Unsaturated	9.1E-02	2.9E-01	9.6E-01	7.6E+00	1.0E+01	1.4E+01	2.2E+01	4.9E+01
Ash	Antimony	7440360	SI	Unsaturated	0.0E+00	1.1E-01	3.4E-01	6.8E-01	7.9E-01	9.5E-01	1.3E+00	1.6E+00
Ash	Arsenic3	22569728	LF	Saturated	5.2E-02	1.5E-01	4.1E-01	6.6E-01	8.0E-01	9.2E-01	1.0E+00	1.1E+00
Ash	Arsenic3	22569728	SI	Saturated	4.1E-02	1.4E-01	4.1E-01	6.8E-01	8.1E-01	9.2E-01	1.0E+00	1.1E+00
Ash	Arsenic3	22569728	LF	Unsaturated	1.5E-01	5.0E-01	1.2E+00	2.2E+00	2.7E+00	3.7E+00	5.8E+00	1.2E+01
Ash	Arsenic3	22569728	SI	Unsaturated	5.7E-05	3.1E-01	7.4E-01	1.3E+00	1.5E+00	1.6E+00	1.8E+00	2.1E+00
Ash	Arsenic5	15584040	LF	Saturated	1.1E+00	7.0E+00	3.4E+01	9.8E+01	1.2E+02	1.6E+02	2.1E+02	6.3E+02
Ash	Arsenic5	15584040	SI	Saturated	1.2E+00	6.7E+00	2.9E+01	8.9E+01	1.1E+02	1.5E+02	2.9E+02	5.9E+02
Ash	Arsenic5	15584040	LF	Unsaturated	0.0E+00	4.2E+00	3.6E+01	1.0E+02	1.3E+02	1.6E+02	2.1E+02	4.2E+02
Ash	Arsenic5	15584040	SI	Unsaturated	2.9E-01	3.2E+00	2.1E+01	7.6E+01	9.5E+01	1.3E+02	2.0E+02	4.7E+02
Ash	Barium	7440393	LF	Saturated	2.4E-01	4.2E-01	5.6E-01	9.2E-01	1.1E+00	1.2E+00	1.6E+00	2.3E+00
Ash	Barium	7440393	SI	Saturated	2.5E-01	4.4E-01	5.7E-01	9.3E-01	1.1E+00	1.2E+00	1.6E+00	2.4E+00
Ash	Barium	7440393	LF	Unsaturated	0.0E+00	7.1E+00	2.0E+02	6.6E+02	7.9E+02	1.0E+03	1.4E+03	2.2E+03
Ash	Barium	7440393	SI	Unsaturated	0.0E+00	8.7E-01	1.8E+00	5.9E+00	8.0E+00	1.2E+01	1.9E+01	5.3E+01
Ash	Boron	7440428	LF	Saturated	3.8E-11	4.3E-10	1.7E-07	2.8E-06	3.6E-06	5.4E-06	7.1E-06	1.0E-05
Ash	Boron	7440428	SI	Saturated	2.6E-10	3.2E-08	1.7E-06	6.5E-06	7.7E-06	8.9E-06	1.1E-05	1.3E-05
Ash	Boron	7440428	LF	Unsaturated	2.6E-03	1.3E-01	4.4E-01	1.8E+00	2.2E+00	2.8E+00	3.9E+00	6.2E+00
Ash	Boron	7440428	SI	Unsaturated	0.0E+00	2.5E-02	1.1E-01	2.2E-01	2.5E-01	3.4E-01	6.6E-01	1.6E+00
Ash	Cadmium	7440439	LF	Saturated	1.6E-01	4.0E-01	7.7E-01	1.8E+00	2.1E+00	3.4E+00	5.1E+00	7.0E+00
Ash	Cadmium	7440439	SI	Saturated	1.6E-01	4.0E-01	7.1E-01	1.7E+00	2.0E+00	3.4E+00	5.1E+00	7.3E+00
Ash	Cadmium	7440439	LF	Unsaturated	2.2E-01	9.8E-01	2.0E+00	4.3E+00	5.2E+00	7.1E+00	9.4E+00	1.3E+01
Ash	Cadmium	7440439	SI	Unsaturated	-4.1E-02	3.1E-01	7.8E-01	2.0E+00	2.7E+00	4.0E+00	6.3E+00	1.0E+01

(continued)

Select Percentiles of K_d Sampled from MINTEQA2 Isotherms by Updated EPACMTP by Waste Type, Metal Species, WMU Type, and Subsurface Domain (continued)

Waste Stream	Metal	CASID	WMU	Zone	Percentiles of K_d							
					10%	25%	50%	75%	80%	85%	90%	95%
Ash	Cobalt	7440484	LF	Saturated	5.2E-01	1.0E+00	4.0E+00	1.6E+01	1.8E+01	3.5E+01	6.1E+01	1.1E+02
Ash	Cobalt	7440484	SI	Saturated	6.5E-01	9.6E-01	2.7E+00	1.1E+01	1.6E+01	2.9E+01	6.7E+01	1.2E+02
Ash	Cobalt	7440484	LF	Unsaturated	2.4E-01	2.6E+00	8.7E+00	2.8E+01	3.5E+01	4.6E+01	7.1E+01	1.1E+02
Ash	Cobalt	7440484	SI	Unsaturated	-2.9E-02	1.3E+00	3.3E+00	1.0E+01	1.3E+01	1.9E+01	3.9E+01	8.7E+01
Ash	Lead	7439921	LF	Saturated	9.0E+00	1.6E+01	2.5E+01	3.9E+01	4.3E+01	5.0E+01	9.7E+01	1.7E+02
Ash	Lead	7439921	SI	Saturated	8.3E+00	1.6E+01	2.2E+01	3.5E+01	4.0E+01	4.5E+01	6.3E+01	1.8E+02
Ash	Lead	7439921	LF	Unsaturated	0.0E+00	2.0E+01	3.3E+01	5.2E+01	5.9E+01	7.0E+01	9.6E+01	1.6E+02
Ash	Lead	7439921	SI	Unsaturated	-1.1E-01	1.3E+00	1.9E+01	3.3E+01	3.6E+01	4.1E+01	4.9E+01	1.3E+02
Ash	Mercury	7439976	LF	Saturated	2.0E-05	1.0E-04	4.4E-04	2.1E-03	2.4E-03	4.6E-03	5.6E-03	9.5E-03
Ash	Mercury	7439976	LF	Unsaturated	8.9E-02	2.0E+00	5.4E+00	1.1E+01	1.3E+01	1.7E+01	2.3E+01	3.7E+01
Ash	Molybdenum	7439987	LF	Saturated	7.8E-07	3.0E-05	1.8E-03	6.0E-02	1.2E-01	2.3E-01	3.7E-01	5.9E-01
Ash	Molybdenum	7439987	SI	Saturated	3.2E-07	3.0E-05	4.3E-03	6.0E-02	1.1E-01	2.1E-01	2.4E-01	4.0E-01
Ash	Molybdenum	7439987	LF	Unsaturated	2.3E-02	1.6E-01	3.4E-01	9.1E-01	1.1E+00	1.5E+00	2.0E+00	3.1E+00
Ash	Molybdenum	7439987	SI	Unsaturated	6.0E-11	5.0E-02	1.6E-01	4.0E-01	5.3E-01	7.0E-01	1.3E+00	1.6E+00
Ash	Nitrate/Nitrite	14797558	LF	Saturated	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Ash	Nitrate/Nitrite	14797558	SI	Saturated	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Ash	Nitrate/Nitrite	14797558	LF	Unsaturated	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Ash	Nitrate/Nitrite	14797558	SI	Unsaturated	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Ash	Selenium4	10026036	LF	Saturated	3.3E-01	7.3E+00	1.5E+02	1.2E+03	2.0E+03	2.9E+03	3.6E+03	5.8E+03
Ash	Selenium4	10026036	SI	Saturated	4.5E-02	2.9E+00	2.4E+02	1.3E+03	2.0E+03	3.0E+03	3.6E+03	5.8E+03
Ash	Selenium4	10026036	LF	Unsaturated	1.8E-01	5.4E+00	1.3E+02	8.6E+02	1.5E+03	2.3E+03	3.2E+03	5.2E+03
Ash	Selenium4	10026036	SI	Unsaturated	0.0E+00	2.0E+00	1.6E+02	9.4E+02	1.7E+03	2.5E+03	3.4E+03	5.6E+03
Ash	Selenium6	7782492	LF	Saturated	5.1E-13	6.3E-11	3.0E-07	2.7E-04	6.7E-04	1.8E-03	2.7E-03	4.9E-03
Ash	Selenium6	7782492	SI	Saturated	7.4E-09	6.8E-07	8.4E-05	9.5E-04	1.4E-03	2.2E-03	3.2E-03	4.5E-03
Ash	Selenium6	7782492	LF	Unsaturated	3.3E-03	1.1E-01	2.0E-01	9.1E-01	1.3E+00	1.7E+00	2.5E+00	4.0E+00
Ash	Selenium6	7782492	SI	Unsaturated	0.0E+00	2.2E-02	1.1E-01	2.1E-01	2.3E-01	2.8E-01	5.0E-01	1.6E+00
Ash	Thallium	7440280	LF	Saturated	1.1E-02	1.7E-02	2.7E-02	4.3E-02	5.2E-02	6.3E-02	8.1E-02	1.1E-01
Ash	Thallium	7440280	SI	Saturated	1.2E-02	1.7E-02	2.5E-02	4.4E-02	5.2E-02	6.6E-02	8.5E-02	1.6E-01

(continued)

Select Percentiles of K_d Sampled from MINTEQA2 Isotherms by Updated EPACMTP by Waste Type, Metal Species, WMU Type, and Subsurface Domain (continued)

Waste Stream	Metal	CASID	WMU	Zone	Percentiles of K_d							
					10%	25%	50%	75%	80%	85%	90%	95%
Ash	Thallium	7440280	LF	Unsaturated	5.5E-02	2.0E-01	4.0E-01	1.5E+00	1.8E+00	2.4E+00	3.2E+00	4.8E+00
Ash	Thallium	7440280	SI	Unsaturated	0.0E+00	8.1E-02	1.7E-01	2.9E-01	3.5E-01	4.9E-01	9.3E-01	1.6E+00
Ash & Coal	Aluminum	7429905	LF	Saturated	1.8E-07	1.8E-07	4.0E-07	1.3E-01	1.3E-01	1.3E-01	3.5E-01	2.8E+00
Ash & Coal	Aluminum	7429905	SI	Saturated	1.8E-07	4.0E-07	7.3E-03	1.9E-01	2.0E-01	8.8E-01	5.8E+00	1.4E+01
Ash & Coal	Aluminum	7429905	LF	Unsaturated	0.0E+00	1.2E-01	1.1E+01	4.7E+01	5.9E+01	7.6E+01	9.8E+01	1.5E+02
Ash & Coal	Aluminum	7429905	SI	Unsaturated	1.4E-02	1.1E-01	2.6E-01	9.4E-01	1.5E+00	1.7E+00	2.9E+00	6.3E+00
Ash & Coal	Antimony	7440360	LF	Saturated	1.8E-03	5.4E-03	1.7E-02	7.3E-02	8.0E-02	1.5E-01	3.2E-01	5.5E-01
Ash & Coal	Antimony	7440360	LF	Unsaturated	0.0E+00	1.8E-01	1.4E+00	6.4E+00	8.2E+00	1.1E+01	1.4E+01	2.2E+01
Ash & Coal	Arsenic3	22569728	LF	Saturated	5.5E-03	1.7E-02	6.4E-02	1.9E-01	2.7E-01	4.6E-01	7.4E-01	9.9E-01
Ash & Coal	Arsenic3	22569728	SI	Saturated	4.6E-03	1.6E-02	5.1E-02	1.4E-01	2.6E-01	4.5E-01	7.1E-01	1.1E+00
Ash & Coal	Arsenic3	22569728	LF	Unsaturated	0.0E+00	1.6E-01	3.8E-01	1.9E+00	2.6E+00	3.6E+00	5.4E+00	9.8E+00
Ash & Coal	Arsenic3	22569728	SI	Unsaturated	3.8E-02	1.1E-01	2.3E-01	6.3E-01	8.8E-01	1.3E+00	1.6E+00	2.1E+00
Ash & Coal	Arsenic5	15584040	LF	Saturated	3.3E-02	7.2E-01	6.3E+00	3.3E+01	4.6E+01	5.4E+01	9.5E+01	3.2E+02
Ash & Coal	Arsenic5	15584040	SI	Saturated	3.3E-02	3.5E-01	2.3E+00	1.4E+01	2.1E+01	2.9E+01	4.8E+01	1.5E+02
Ash & Coal	Arsenic5	15584040	LF	Unsaturated	0.0E+00	4.8E-01	6.4E+00	3.4E+01	4.6E+01	6.3E+01	9.8E+01	2.2E+02
Ash & Coal	Arsenic5	15584040	SI	Unsaturated	1.9E-01	9.6E-01	3.5E+00	1.6E+01	2.2E+01	3.2E+01	5.1E+01	1.3E+02
Ash & Coal	Barium	7440393	LF	Saturated	3.7E-02	4.5E-02	2.3E-01	1.3E+00	1.3E+00	1.5E+00	1.9E+00	2.2E+00
Ash & Coal	Barium	7440393	SI	Saturated	1.3E-02	4.5E-02	1.8E-01	1.3E+00	1.3E+00	1.5E+00	2.1E+00	2.2E+00
Ash & Coal	Barium	7440393	LF	Unsaturated	0.0E+00	4.6E-01	1.5E+01	5.0E+01	6.2E+01	7.4E+01	1.0E+02	1.6E+02
Ash & Coal	Barium	7440393	SI	Unsaturated	5.2E-02	5.0E-01	2.4E+00	9.6E+00	1.4E+01	2.1E+01	3.7E+01	5.4E+01
Ash & Coal	Boron	7440428	LF	Saturated	7.1E-08	2.1E-07	8.1E-07	2.4E-06	3.5E-06	5.9E-06	9.5E-06	1.3E-05
Ash & Coal	Boron	7440428	SI	Saturated	6.0E-08	2.1E-07	6.3E-07	1.8E-06	3.6E-06	6.4E-06	1.0E-05	1.5E-05
Ash & Coal	Boron	7440428	LF	Unsaturated	0.0E+00	5.2E-02	1.5E-01	2.2E-01	2.5E-01	3.2E-01	4.4E-01	6.9E-01
Ash & Coal	Boron	7440428	SI	Unsaturated	7.9E-07	3.1E-02	1.1E-01	2.0E-01	2.3E-01	2.8E-01	5.6E-01	1.6E+00
Ash & Coal	Cadmium	7440439	LF	Saturated	1.7E-03	4.6E-02	1.5E-01	7.7E-01	1.0E+00	2.1E+00	2.9E+00	4.7E+00
Ash & Coal	Cadmium	7440439	SI	Saturated	1.7E-03	4.6E-02	8.5E-02	6.1E-01	1.0E+00	2.1E+00	3.2E+00	4.5E+00
Ash & Coal	Cadmium	7440439	LF	Unsaturated	0.0E+00	2.6E-01	7.9E-01	2.2E+00	2.7E+00	3.9E+00	5.9E+00	9.0E+00
Ash & Coal	Cadmium	7440439	SI	Unsaturated	6.4E-02	1.7E-01	4.0E-01	1.6E+00	2.2E+00	3.3E+00	4.4E+00	7.1E+00

(continued)

Select Percentiles of K_d Sampled from MINTEQA2 Isotherms by Updated EPACMTP by Waste Type, Metal Species, WMU Type, and Subsurface Domain (continued)

Waste Stream	Metal	CASID	WMU	Zone	Percentiles of K_d							
					10%	25%	50%	75%	80%	85%	90%	95%
Ash & Coal	Cobalt	7440484	LF	Saturated	7.6E-03	6.6E-02	5.8E-01	2.8E+00	3.2E+00	5.4E+00	8.5E+00	2.9E+01
Ash & Coal	Cobalt	7440484	SI	Saturated	7.6E-03	6.5E-02	2.1E-01	2.4E+00	2.9E+00	4.1E+00	6.1E+00	1.1E+01
Ash & Coal	Cobalt	7440484	LF	Unsaturated	0.0E+00	7.9E+00	3.1E+01	9.3E+01	1.1E+02	1.5E+02	2.9E+02	5.7E+02
Ash & Coal	Cobalt	7440484	SI	Unsaturated	2.3E-01	4.5E-01	1.7E+00	4.9E+00	5.9E+00	7.3E+00	1.1E+01	2.1E+01
Ash & Coal	Lead	7439921	LF	Saturated	1.1E-01	2.3E+00	6.6E+00	2.1E+01	2.9E+01	3.8E+01	4.1E+01	6.3E+01
Ash & Coal	Lead	7439921	SI	Saturated	1.1E-01	2.3E+00	3.7E+00	2.2E+01	2.9E+01	3.9E+01	4.4E+01	6.3E+01
Ash & Coal	Lead	7439921	LF	Unsaturated	0.0E+00	4.4E+00	1.4E+01	4.1E+01	4.9E+01	5.6E+01	7.1E+01	1.2E+02
Ash & Coal	Lead	7439921	SI	Unsaturated	-6.3E-03	9.5E-01	4.5E+00	2.0E+01	3.0E+01	3.9E+01	4.6E+01	6.4E+01
Ash & Coal	Mercury	7439976	LF	Saturated	9.0E-04	2.1E-03	1.3E-02	7.9E-02	3.3E-01	6.8E-01	2.9E+00	4.3E+00
Ash & Coal	Mercury	7439976	SI	Saturated	1.7E-03	3.3E-03	6.2E-02	8.8E-01	1.5E+00	2.8E+00	2.9E+00	4.3E+00
Ash & Coal	Mercury	7439976	LF	Unsaturated	0.0E+00	1.6E+00	6.3E+00	1.5E+01	1.8E+01	2.2E+01	3.0E+01	4.4E+01
Ash & Coal	Mercury	7439976	SI	Unsaturated	4.8E-02	1.5E-01	3.6E-01	1.6E+00	1.6E+00	2.1E+00	3.0E+00	4.4E+00
Ash & Coal	Molybdenum	7439987	LF	Saturated	3.4E-06	6.7E-05	2.5E-03	4.6E-02	7.5E-02	1.6E-01	2.7E-01	7.1E-01
Ash & Coal	Molybdenum	7439987	SI	Saturated	3.4E-06	3.1E-04	1.1E-02	7.5E-02	7.5E-02	1.6E-01	3.1E-01	9.4E-01
Ash & Coal	Molybdenum	7439987	LF	Unsaturated	0.0E+00	7.3E-02	2.1E-01	7.7E-01	1.0E+00	1.4E+00	2.0E+00	2.9E+00
Ash & Coal	Molybdenum	7439987	SI	Unsaturated	4.7E-03	8.3E-02	2.0E-01	5.0E-01	7.6E-01	1.3E+00	1.6E+00	2.2E+00
Ash & Coal	Nitrate/Nitrite	14797558	LF	Saturated	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Ash & Coal	Nitrate/Nitrite	14797558	SI	Saturated	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Ash & Coal	Nitrate/Nitrite	14797558	LF	Unsaturated	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Ash & Coal	Nitrate/Nitrite	14797558	SI	Unsaturated	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Ash & Coal	Selenium4	10026036	LF	Saturated	3.7E-01	6.1E+00	5.3E+01	5.3E+02	8.5E+02	1.1E+03	1.9E+03	6.5E+03
Ash & Coal	Selenium4	10026036	SI	Saturated	3.7E-01	1.6E+01	1.2E+02	7.7E+02	9.1E+02	1.4E+03	3.3E+03	7.3E+03
Ash & Coal	Selenium4	10026036	LF	Unsaturated	0.0E+00	2.9E+00	4.4E+01	3.2E+02	5.5E+02	8.7E+02	1.5E+03	5.1E+03
Ash & Coal	Selenium4	10026036	SI	Unsaturated	4.7E-01	1.0E+01	1.0E+02	6.1E+02	8.6E+02	1.1E+03	2.9E+03	7.0E+03
Ash & Coal	Selenium6	7782492	LF	Saturated	2.9E-08	7.7E-08	1.8E-05	6.4E-04	1.1E-03	1.4E-03	3.2E-03	8.8E-03
Ash & Coal	Selenium6	7782492	SI	Saturated	4.7E-08	3.2E-06	1.1E-04	9.6E-04	1.1E-03	1.6E-03	5.1E-03	1.0E-02
Ash & Coal	Selenium6	7782492	LF	Unsaturated	0.0E+00	5.9E-02	1.6E-01	7.0E-01	1.0E+00	1.5E+00	2.3E+00	3.7E+00
Ash & Coal	Selenium6	7782492	SI	Unsaturated	1.7E-03	5.2E-02	1.3E-01	2.6E-01	3.4E-01	5.6E-01	1.2E+00	1.6E+00

(continued)

Select Percentiles of K_d Sampled from MINTEQA2 Isotherms by Updated EPACMTP by Waste Type, Metal Species, WMU Type, and Subsurface Domain (continued)

Waste Stream	Metal	CASID	WMU	Zone	Percentiles of K_d							
					10%	25%	50%	75%	80%	85%	90%	95%
Ash & Coal	Thallium	7440280	LF	Saturated	2.9E-04	1.9E-03	9.8E-03	2.0E-02	2.4E-02	3.7E-02	5.0E-02	7.7E-02
Ash & Coal	Thallium	7440280	LF	Unsaturated	0.0E+00	1.2E-01	3.9E-01	1.3E+00	1.7E+00	2.1E+00	2.7E+00	3.9E+00
FBC	Aluminum	7429905	LF	Saturated	4.1E-25	4.6E-25	1.4E-17	5.2E-08	1.7E-07	1.7E-07	5.3E-07	7.1E-03
FBC	Aluminum	7429905	LF	Unsaturated	0.0E+00	1.5E-01	2.5E-01	4.6E+02	8.6E+02	1.9E+03	3.9E+03	8.7E+03
FBC	Antimony	7440360	LF	Saturated	3.0E-04	1.2E-02	2.0E-02	6.9E-02	8.7E-02	1.1E-01	1.4E-01	2.3E-01
FBC	Antimony	7440360	LF	Unsaturated	0.0E+00	2.1E-01	4.1E-01	2.2E+00	3.0E+00	4.3E+00	7.2E+00	1.8E+01
FBC	Arsenic3	22569728	LF	Saturated	4.5E-02	1.0E-01	3.9E-01	5.0E-01	6.1E-01	6.4E-01	6.6E-01	6.7E-01
FBC	Arsenic3	22569728	LF	Unsaturated	0.0E+00	4.6E-01	1.1E+00	2.1E+00	7.0E+00	1.6E+01	3.4E+01	1.5E+02
FBC	Arsenic5	15584040	LF	Saturated	3.3E+00	1.0E+01	3.4E+01	7.3E+01	9.3E+01	9.4E+01	1.6E+02	2.4E+02
FBC	Arsenic5	15584040	LF	Unsaturated	0.0E+00	1.1E+01	3.8E+01	8.2E+01	9.9E+01	1.1E+02	1.7E+02	2.5E+02
FBC	Barium	7440393	LF	Saturated	1.6E-01	2.1E-01	4.6E-01	1.4E+00	5.7E+00	7.8E+00	9.3E+00	1.1E+01
FBC	Barium	7440393	LF	Unsaturated	0.0E+00	7.7E+00	7.1E+01	2.7E+02	3.7E+02	4.7E+02	6.3E+02	1.0E+03
FBC	Boron	7440428	LF	Saturated	5.5E-07	1.3E-06	4.9E-06	6.3E-06	7.8E-06	8.1E-06	8.2E-06	8.7E-06
FBC	Boron	7440428	LF	Unsaturated	0.0E+00	1.6E-01	2.6E-01	2.0E+00	2.5E+00	3.2E+00	4.6E+00	8.2E+00
FBC	Cadmium	7440439	LF	Saturated	2.0E-01	2.5E-01	5.9E-01	2.7E+00	3.3E+00	3.4E+00	4.0E+00	5.3E+00
FBC	Cadmium	7440439	LF	Unsaturated	0.0E+00	9.5E-01	2.4E+00	6.3E+00	7.3E+00	8.5E+00	1.0E+01	2.1E+01
FBC	Cobalt	7440484	LF	Saturated	4.7E-01	1.1E+00	5.8E+00	4.4E+01	4.6E+01	7.0E+01	7.3E+01	9.5E+01
FBC	Cobalt	7440484	LF	Unsaturated	0.0E+00	2.2E+00	8.9E+00	4.1E+01	5.5E+01	7.3E+01	9.0E+01	1.1E+02
FBC	Lead	7439921	LF	Saturated	6.8E+00	9.9E+00	2.1E+01	6.9E+01	1.1E+02	1.2E+02	1.7E+02	1.8E+02
FBC	Lead	7439921	LF	Unsaturated	0.0E+00	1.3E+01	2.5E+01	8.3E+01	1.0E+02	1.3E+02	1.5E+02	2.0E+02
FBC	Mercury	7439976	LF	Saturated	1.6E-05	4.2E-05	2.2E-04	1.6E-03	3.1E-03	4.4E-03	5.8E-03	7.0E-03
FBC	Mercury	7439976	LF	Unsaturated	0.0E+00	1.1E+00	6.7E+00	1.9E+01	2.8E+01	4.5E+01	7.8E+01	2.1E+02
FBC	Molybdenum	7439987	LF	Saturated	7.5E-07	8.0E-06	1.3E-04	3.1E-03	7.8E-03	1.3E-02	2.7E-02	4.5E-02
FBC	Molybdenum	7439987	LF	Unsaturated	0.0E+00	1.5E-01	2.3E-01	6.7E-01	9.6E-01	1.3E+00	1.9E+00	3.7E+00
FBC	Nitrate/Nitrite	14797558	LF	Saturated	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
FBC	Nitrate/Nitrite	14797558	LF	Unsaturated	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
FBC	Selenium4	10026036	LF	Saturated	6.4E-02	1.2E+00	1.8E+01	1.2E+02	2.8E+02	4.8E+02	8.8E+02	1.4E+03
FBC	Selenium4	10026036	LF	Unsaturated	0.0E+00	2.1E+00	1.9E+01	1.5E+02	2.9E+02	4.8E+02	7.9E+02	1.3E+03

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Select Percentiles of K_d Sampled from MINTEQA2 Isotherms by Updated EPACMTP by Waste Type, Metal Species, WMU Type, and Subsurface Domain (continued)

Waste Stream	Metal	CASID	WMU	Zone	Percentiles of K_d							
					10%	25%	50%	75%	80%	85%	90%	95%
FBC	Selenium6	7782492	LF	Saturated	1.7E-08	1.8E-07	2.9E-06	5.9E-05	1.4E-04	2.3E-04	3.8E-04	6.9E-04
FBC	Selenium6	7782492	LF	Unsaturated	0.0E+00	1.4E-01	2.3E-01	1.6E+00	2.3E+00	3.5E+00	7.6E+00	2.1E+01
FBC	Thallium	7440280	LF	Saturated	9.5E-03	1.5E-02	2.3E-02	5.1E-02	5.3E-02	6.2E-02	1.1E-01	2.3E-01
FBC	Thallium	7440280	LF	Unsaturated	0.0E+00	2.3E-01	6.2E-01	1.9E+00	2.2E+00	2.7E+00	3.3E+00	5.0E+00

D.7 References

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Appendix E. Surface Water, Fish Concentration, and Contaminant Intake Equations

This appendix presents the equations used to model surface water and fish concentrations and intake of drinking water and fish. These equations are presented in the following attachments:

- **Attachment E-1** provides the equations comprising the surface water equilibrium partitioning model, including equations that estimate steady state concentrations in the water column (dissolved and total) and sediments.
- **Attachment E-2** provides the equations that use bioconcentration factors (BCFs) to calculate fish tissue concentrations from total.
- **Attachment E-3** provides the equations used to calculate daily contaminant intake rates from drinking water and fish consumption.

E.1 Aluminum Surface Water Precipitation

Because the fate and transport of aluminum is controlled more by solubility than by sorption in surface water, the surface water model includes algorithms to estimate aluminum concentrations in the water column and sediments by accounting for precipitation and fallout of aluminum in the water column. These calculations proceed in a stepwise fashion, as follows.

Step 1. Initially, assume all influent aluminum is dissolved in the water column.

Fraction in water column (fwater) = 1
Fraction in sediment layer (fbenth) = 0
Fraction dissolved (fd) = 1

Total water column concentration (Cwctot) = dissolved water column concentration (Cwd).

Step 2. Compare the dissolved water column concentration (Cwd) to the maximum soluble concentration (Csol) calculated in MINTEQA2 for the waterbody pH (see **Section 3.5.4**, Table 3-6 for aluminum solubilities and **Section C.6.3**, Table C-11 for waterbody pH).

Step 3. If the dissolved water concentration (Cwd) is greater than the solubility limit (Csol), reset the dissolved water concentration to the solubility limit, and precipitate and settle out the excess aluminum to the benthic sediment layer.

```
If Cwctot > Csol, then
        Fwater  =  Csol / Cwctot
        Fbenth  =  (Cwctot - Csol) / Cwctot
          Cwbs  =  (Cwctot - Csol) * dwc / db
         Cwtot  =  Cwctot * dwc / dz
           Cdw  =  Csol
        Cwctot  =  Csol
Else
           Cdw  =  Cwctot
          Cwbs  =  0
         Cwtot  =  Cwctot * rsParam!dwc / rsParam!dz
End If
```

where:

Cdw	=	issolved waterbody concentration
Csol	=	maximum soluble concentration
Cwbs	=	total concentration in bed sediment
Cwtot	=	total waterbody concentration from loading
db	=	depth of the upper benthic layer
dwc	=	depth of the water column
dz	=	depth of the waterbody
fbenth	=	fraction in sediment layer
fd	=	fraction dissolved
fwater	=	fraction in water column.

Table E-1-1. Fraction of Contaminant in Water Column (Unitless)

f_{Water}

$$d_w = d_z - d_b$$

$$f_{Water} = \frac{\left[1 - \left(K_{dsw} \times TSS \times 0.000001\right)\right] \times \frac{d_w}{d_z}}{\left[\left[1 - \left(K_{dsw} \times TSS \times 0.000001\right)\right] \times \frac{d_w}{d_z}\right] + \left[\left(bsp + K_{dbs} \times bsc\right) \times \frac{d_b}{d_z}\right]}$$

Name	Description	Value
bsc	Bed sediment particle concentration (g/cm^3) or (kg/L)	1
bsp	Bed sediment porosity (cm^3/cm^3)	0.6
d_b	Depth of upper benthic layer (m)	0.03
d_w	Depth of water column (m)	Site Data; See Appendix C
d_z	Depth of the waterbody (m)	Calculated
K_{dbs}	Sediment-water partition coefficient (mL/g)	Chemical Data; See Section 3
K_{dsw}	Suspended sediment-water partition coefficient (mL/g)	Chemical Data; See Section 3
TSS	Total suspended solids (mg/L)	Site Data; See Appendix C
0.000001	Conversion factor (L/mL)(g/mg)	

Table E-1-2. Fraction of Contaminant in Benthic Sediments (Unitless)

f_{Benth}

$$f_{Benth} = \frac{(bsp + K_{dbs} \times bsc) \times \frac{d_b}{d_z}}{\left[(1 + K_{dsw} \times TSS \times 0.000001) \times \frac{d_W}{d_z}\right] + \left[(bsp + K_{dbs} \times bsc) \times \frac{d_b}{d_z}\right]}$$

Name	Description	Value
bsc	Bed sediment particle concentration (g/cm^3) or (kg/L)	1
bsp	Bed sediment porosity (cm^3/cm^3)	0.6
d_b	Depth of upper benthic layer (m)	0.03
d_w	Depth of water column (m)	Site Data; See Appendix C
d_z	Depth of the waterbody (m)	Calculated
K_{dbs}	Sediment-water partition coefficient (mL/g)	Chemical Data; See Section 3
K_{dsw}	Suspended sediment-water partition coefficient (mL/g)	Chemical Data; See Section 3
TSS	Total suspended solids (mg/L)	Site Data; See Appendix C
0.000001	Conversion factor (L/mL)(g/mg)	

Table E-1-3. Dissolved Fraction (Unitless)

f_d

$$f_d = \frac{1}{1 + K_{dsw} \times TSS \times 0.000001}$$

Name	Description	Value
K_{dsw}	Suspended sediment-water partition coefficient (mL/g)	Chemical Data; See Section 3
TSS	Total suspended solids (mg/L)	Site Data; See Appendix C
0.000001	Conversion factor (L/mL)(g/mg)	

Table E-1-4. Liquid-Phase Transfer Coefficient - Lakes (m/day) (Mercury Only)

KL_{lakes}

$$KL_{Lakes} = \sqrt{C_d} \times u_w \times \sqrt{\frac{R_a}{R_w}} \times \frac{k^{0.33}}{L_2} \times \left(\frac{{}_w}{R_w \times D_w} \right)^{-0.67} \times 86400$$

Name	Description	Value
C_d	Drag coefficient (unitless)	0.0011
D_w	Diffusivity in water (cm^2/s)	Chemical Data; See Section 3, Table 3-4
k	von Karman's constant (unitless)	0.4
L_2	Viscous sublayer thickness (unitless)	4
w	Viscosity of water (g/cm-s)	0.0169
R_a	Density of air (g/cm^3)	0.0012
R_w	Density of water (g/cm^3)	1
u_w	Mean annual wind speed (m/sec)	Site Data; See Appendix C
86400	Conversion factor (sec/day)	

Table E-1-5. Liquid-Phase Transfer Coefficient - Rivers (m/day) (Mercury Only)

KL_{rivers}

$$KL_{Rivers} = \sqrt{\frac{D_w \times U \times 0.0001}{d_z}} \times 86400$$

Name	**Description**	**Value**
D_w	Diffusivity in water (cm^2/s)	Chemical Data; See Section 3, Table 3-4
d_z	Depth of the waterbody (m)	Calculated
U	Current velocity of the waterbody (m/s)	Site Data; See Appendix C
86400	Conversion factor (sec/day)	

Table E-1-6. Gas-Phase Transfer Coefficient - Lakes (m/day) (Mercury Only)

K_{gas}

$$K_{gas} = \sqrt{C_d} \times u_w \times \frac{k^{0.33}}{L_2} \times \left(\frac{a}{R_a \times D_a} \right)^{-0.67} \times 86400$$

Name	Description	Value
C_d	Drag coefficient (unitless)	0.0011
D_a	Diffusivity of chemical in air (cm^2/s)	Chemical Data; See Section 3, Table 3-4
k	von Karman's constant (unitless)	0.4
L_2	Viscous sublayer thickness (unitless)	4
A	Viscosity of air (g/cm-s)	0.000181
R_a	Density of air (g/cm^3)	0.0012
u_w	Mean annual wind speed (m/sec)	Site Data; See Appendix C
86400	Conversion factor (sec/day)	

Table E-1-7. Diffusion Transfer Rate (m/day) (Mercury Only)

K_v

$$Tempadjust = \theta_{water}^{(T_w - T_{hlc})}$$

$$K_v = \frac{1}{\frac{1}{K_L} + \frac{1}{K_g \times H'}} \times TempAdjust$$

$$H' = \frac{HLC}{R \times T_w}$$

Name	Description	Value
HLC	Henry's Law constant (atm-m^3/mole	Chemical Data; See Section 3, Table 3-4
H'	Dimensionless Henry's Law constant (unitless)	Calculated
K_g	Gas-Phase Transfer Coefficient (m/d)	Calculated
K_L	Liquid-Phase Transfer Coefficient (m/d)	Calculated
R	Ideal Gas Constant (atm-m^3/K-mole)	0.00008205
θ_{water}	Temperature correction (unitless)	1.026
T_{hlc}	Temperature of HLC (K)	298
T_w	Temperature of the waterbody (K)	Site Data; See Appendix C

Note: Drawn from U.S. EPA, 1998 (EPA-530-D-98-001A and EPA-600/R-98/137).

Table E-1-8. Water Concentration Dissipation Rate Constant (1/day)

K_{wt}

$$K_{wt} = (f_{Water} \times f_d \times k_{vol}) + (f_{benth} \times K_b) + (f_{Water} \times k_{sw}) + (f_{benth} \times k_{sed}) + k_h$$

$$K_b = \frac{WB}{d_b}$$

$$k_{vol} = \frac{K_v}{d_w}$$

Name	Description	Value
d_b	Depth of upper benthic layer (m)	0.03
d_w	Depth of water column (m)	Site Data; See Appendix C
F_{benth}	Fraction of contaminant in benthic sediments (unitless)	Calculated
f_d	Dissolved fraction (unitless)	Calculated
f_{Water}	Fraction of contaminant in water column (unitless)	Calculated
K_b	Benthic burial rate constant (1/day)	Calculated
k_h	Hydrolysis rate (1/day)	0
k_{sed}	Degradation rate for sediment (1/day)	0
k_{sw}	Degradation rate for water column (1/day)	0
K_v	Diffusion transfer rate (m/day)	Calculated (mercury only)
k_{vol}	Water column volatilization rate constant (1/day)	Calculated (mercury only)
WB	Rate of Burial (m/day)	0

Table E-1-7. Diffusion Transfer Rate (m/day) (Mercury Only)

K_v

$$Tempadjust = \theta_{water}^{(T_w - T_{hlc})}$$

$$K_v = \frac{1}{\frac{1}{K_L} + \frac{1}{K_g \times H'}} \times TempAdjust$$

$$H' = \frac{HLC}{R \times T_w}$$

Name	Description	Value
HLC	Henry's Law constant (atm-m^3/mole	Chemical Data; See Section 3, Table 3-4
H'	Dimensionless Henry's Law constant (unitless)	Calculated
K_g	Gas-Phase Transfer Coefficient (m/d)	Calculated
K_L	Liquid-Phase Transfer Coefficient (m/d)	Calculated
R	Ideal Gas Constant (atm-m^3/K-mole)	0.00008205
θ_{water}	Temperature correction (unitless)	1.026
T_{hlc}	Temperature of HLC (K)	298
T_w	Temperature of the waterbody (K)	Site Data; See Appendix C

Note: Drawn from U.S. EPA, 1998 (EPA-530-D-98-001A and EPA-600/R-98/137).

Table E-1-10. Total Water Column Concentration (g/m^3 or mg/L)

C_{wcTot}

$$d_w = d_z - d_b$$

$$C_{wcTot} = C_{wTot} \times f_{water} \times \frac{d_z}{d_w}$$

Name	Description	Value
Cw_{Tot}	Total Waterbody Concentration from Loading (g/m^3 or mg/L)	Calculated
d_b	Depth of upper benthic layer (m)	0.03
d_w	Depth of water column (m)	Site Data; See Appendix C
d_z	Depth of the waterbody (m)	Calculated
f_{Water}	Fraction of contaminant in water column (unitless)	Calculated

Table E-1-11. Dissolved Waterbody Concentration (mg/L)

C_{dw}

$$d_w = d_z - d_b$$

$$C_{dw} = Cw_{Tot} \times f_{Water} \times f_d \times \frac{d_Z}{d_w}$$

Name	Description	Value
Cw_{Tot}	Total Waterbody Concentration from Loading (g/m^3 or mg/L)	Calculated
d_b	Depth of upper benthic layer (m)	0.03
d_w	Depth of water column (m)	Site Data; See Appendix C
d_z	Depth of the waterbody (m)	Calculated
f_d	Dissolved fraction (unitless)	Calculated
f_{Water}	Fraction of contaminant in water column (unitless)	Calculated

Table E-1-12. Total Concentration in Bed Sediment (g/m^3 or mg/L)

C_{wbs}

$$d_z = d_w + d_b$$

$$C_{bs} = C_{wTot} \times f_{benth} \times \frac{d_z}{d_b}$$

Name	Description	Value
Cw_{Tot}	Total Waterbody Concentration from Loading (g/m^3 or mg/L)	Calculated
d_b	Depth of upper benthic layer (m)	0.03
d_w	Depth of water column (m)	Site Data; See Appendix C
d_z	Depth of the waterbody (m)	Calculated

Table E-2-1. Concentration in Fish at Different Trophic Levels (mg/kg)

C_{fish}

For Mercury:

$$C_{fish} = 0.15 * C_{dw} \times BCF$$

For Non-Volatile Metals:

$$C_{fish} = Cw_{tot} \times BCF$$

Name	Description	Value
BCF	Bioconcentration factor for specified trophic level (L/kg)	Chemical Data; See Section 3
C_{dw}	Dissolved waterbody concentration (mg/L)	Calculated
Cw_{Tot}	Total waterbody concentration from loading (g/m^3 or mg/L)	Calculated
0.15	Fraction of dissolved mercury assumed to be methyl mercury (unitless)	

Table E-2-2. Average Fish Fillet Concentration Ingested by Humans (mg/kg)

C_{fish_fillet}

$$C_{fish_fillet} = F_{T3} \times C_{fishT3F} + F_{T4} \times C_{fishT4F}$$

Name	Description	Value
$C_{fishT3F}$	Concentration of contaminant in fish at different trophic levels (mg/kg)	Calculated
$C_{fishT4F}$	Concentration of contaminant in fish at different trophic levels (mg/kg)	Calculated
F_{T3}	Fraction of trophic level 3 intake (unitless)	0.36
F_{T4}	Fraction of trophic level 4 intake (unitless)	0.64

Table E-3-1. Contaminant Intake from Drinking Water (mg/kg-d)

Idw

$$I_{dw} = \frac{C_{dw} \times CR_{dw} \times F_{dw}}{BW * 1000}$$

Name	Description	Value
BW	Body weight (kg)	Exposure Data; See Appendix F
C_{dw}	Dissolved waterbody concentration (mg/L)	Calculated
CR_{dw}	Consumption rate of water (mL/day)	Exposure Data; See Appendix F
F_{dw}	Fraction of drinking water ingested that is contaminated (unitless)	1
1000	Conversion factor (mL/L)	

Table E-3-2. Daily Intake of Contaminant from Fish Ingestion (mg/kg BW/day)

I_{fish}

$$I_{fish} = \frac{C_{fish_fillet} \times CR_{fish} \times F_{fish}}{1000 \times BW}$$

Name	**Description**	**Value**
BW	Body weight (kg)	Exposure Data; See Appendix F
C_{fish_fillet}	Average fish fillet concentration ingested by humans (mg/kg)	Calculated
CR_{fish}	Consumption rate of fish (g WW/day)	Exposure Data; See Appendix F
F_{fish}	Fraction of fish intake from contaminated source (unitless)	1
1000	Conversion factor (g/kg)	

Appendix F. Human Exposure Factors

Exposure factors are data that quantify human behavior patterns (e.g., ingestion rates of fish and drinking water) and characteristics (e.g., body weight) that affect a person's exposure to environmental contaminants. These data can be used to construct realistic assumptions concerning an individual's exposure to and subsequent intake of a contaminant in the environment. The exposure factors data also enable EPA to differentiate the exposures of individuals of different ages (e.g., a child vs. an adult). The derivation and values used for the human exposure factors in this risk assessment are described below, and the exposure factors selected for the probabilistic analyses are also presented.

F.1 Exposure Parameters Used in Probabilistic Analysis

F.1.1 Introduction

The general methodology for collecting human exposure data for the probabilistic analysis relied on the *Exposure Factors Handbook*, or EFH (U.S. EPA, 1997a-c), which was used in one of three ways:

1. When EFH percentile data were adequate (most input variables), maximum likelihood estimation was used to fit selected parametric models (gamma, lognormal, Weibull, and generalized gamma) to the EFH data. The chi-square measure of goodness of fit was then used to choose the best distribution. Parameter uncertainty information (e.g., for averages, standard deviations) also was derived using the asymptotic normality of the maximum likelihood estimate or a regression approach.

2. When EFH percentile data were not adequate for statistical model fitting (a few variables), models were selected on the basis of results for other age cohorts or, if no comparable information was available, by assuming lognormal as a default distribution and reasonable coefficients of variation (CVs).

3. When data were not adequate for either 1 or 2 above, variables were fixed at EFH-recommended mean values or according to established EPA policy.

Table F-1 lists all of the parameters used in the probabilistic analysis. Both fixed variables and the values used to define distributed data are provided.

Probabilistic risk analyses involve "sampling" values from probability distribution functions (PDFs) and using the values to estimate risk. In some cases, distributions are infinite, and there is a probability, although very small, that very large or very small values might be selected from the distributions. Because selecting extremely large or extremely small values is unrealistic (e.g., the range of adult body weights is not infinite), maximum and minimum values

were imposed on the distributions. The minimum and maximum values are included in Table F-1.

F.1.2 Exposure Parameter Distribution Methodology

This section describes how stochastic or distributed input data for each exposure factor were collected and processed. Exposure parameter distributions were developed for use in the Monte Carlo analysis. For most variables for which distributions were developed, exposure factor data from the EFH were analyzed to fit selected parametric models (i.e., gamma, lognormal, Weibull). Steps in the development of distributions included preparing data, fitting models, assessing fit, and preparing parameters to characterize distributional uncertainty in the model inputs.

For many exposure factors, EFH data include sample sizes and estimates of the following parameters for specific receptor types and age groups: mean, standard deviation, standard error, and percentiles corresponding to a subset of the following probabilities: 0.01, 0.02, 0.05, 0.10, 0.15, 0.25, 0.50, 0.75, 0.85, 0.90, 0.95, 0.98, and 0.99. These percentile data, where available, were used as a basis for fitting distributions. Although in no case were all of these percentiles actually provided for a single factor, seven or more are typically present in the EFH data. Therefore, using the percentiles was a fuller use of the available information than fitting distributions simply based on the method of moments (e.g., selecting models that agree with the data mean and standard deviation). For some factors, certain percentiles were not used in the fitting process because sample sizes were too small to justify their use. Percentiles were used only if at least one data point was in the tail of the distribution. If the EFH data repeated a value across several adjacent percentiles, only one value (the most central or closest to the median) was used in most cases (e.g., if both the 98th and 99th percentiles had the same value, only the 98th percentile value was used).

The EFH does not use standardized age cohorts across exposure factors. Data for different exposure factors are reported for different age categories. Therefore, to obtain the percentiles for fitting the four standardized age cohorts (i.e., ages 1 to 5, 6 to 11, 12 to 19, and more than 20), each EFH cohort-specific value for a given exposure factor was assigned to one of these four cohorts. When multiple EFH cohorts fitted into a single CCW cohort, the EFH percentiles were averaged within each CCW cohort (e.g., data on 1- to 2-year-olds and 3- to 5-year-olds from EFH were averaged for the CCW 1- to 5-year-old cohort). If sample sizes were available, weighted averages were used, with weights proportional to sample sizes. If sample sizes were not available, equal weights were assumed (i.e., the percentiles were simply averaged).

Table F-1. Summary of Exposure Parameters Used in Probabilistic Analysis

Parameter	Units	Variable Type	Constants	Mean (or shape)	Std Dev (or scale)	Minimum	Maximum	Reference
Averaging time for carcinogens	yr	Constant	7.00E+01					U.S. EPA (1989)
Body weight (adult)	kg	Lognormal		7.12E+01	1.33E+01	1.50E+01	3.00E+02	U.S. EPA (1997a); Tables 7-2, 7-4, 7-5
Body weight (child 1)	kg	Lognormal		1.55E+01	2.05E+00	4.00E+00	5.00E+01	U.S. EPA (1997a); Tables 7-3, 7-6, 7-7
Body weight (child 2)	kg	Lognormal		3.07E+01	5.96E+00	6.00E+00	2.00E+02	U.S. EPA (1997a); Tables 7-3, 7-6, 7-7
Body weight (child 3)	kg	Lognormal		5.82E+01	1.02E+01	1.30E+01	3.00E+02	U.S. EPA (1997a); Tables 7-3, 7-6, 7-7
Consumption rate: fish (adult, child)	g/d	Lognormal		6.48E+00	1.99E+01	0.00E+00	1.50E+03	U.S. EPA (1997b); Table 10-64
Exposure duration (adult resident)	yr	Weibull		1.34E+00	1.74E+01	1.00E+00	5.00E+01	U.S. EPA (1999) (ACS)
Exposure duration (child)	yr	Weibull		1.32E+00	7.06E+00	1.00E+00	5.00E+01	U.S. EPA (1999) (ACS)
Exposure frequency (adult resident)	d/yr	Constant	3.50E+02					U.S. EPA Policy
Fraction contaminated: drinking water	Fraction	Constant	1.00E+00					U.S. EPA Policy
Fraction contaminated: fish	Fraction	Constant	1.00E+00					U.S. EPA Policy
Fraction of fish consumed that is trophic level (T3) fish	Fraction	Constant	3.60E-01					U.S. EPA (1997b); Table 10-66
Fraction of fish consumed that is trophic level 4 (T4) fish	Fraction	Constant	6.40E-01					U.S. EPA (1997b); Table 10-66
Ingestion rate: drinking water (adult resident)	mL/d	Gamma		3.88E+00	3.57E+02	1.04E+02	1.10E+04	U.S. EPA (1997a); Table 3-6
Ingestion rate: drinking water (child 1 resident)	mL/d	Gamma		2.95E+00	2.37E+02	2.60E+01	3.84E+03	U.S. EPA (1997a); Table 3-6
Ingestion rate: drinking water (child 2 resident)	mL/d	Gamma		3.35E+00	2.35E+02	3.40E+01	4.20E+03	U.S. EPA (1997a); Table 3-6
Ingestion rate: drinking water (child 3 resident)	mL/d	Gamma		2.82E+00	3.42E+02	3.30E+01	5.40E+03	U.S. EPA (1997a); Table 3-6

Because the EFH data are always positive and are almost always skewed to the right (i.e., have a long right tail), three two-parameter probability models commonly used to characterize such data (gamma, lognormal, and Weibull) were selected. In addition, a three-parameter model (generalized gamma) was used that unifies them[1] and allows for a likelihood ratio test of the fit of the two-parameter models. However, only the two-parameter models were selected for use in the analysis because the three-parameter generalized gamma model did not significantly improve the goodness of fit over the two-parameter models. This simple setup constitutes a considerable improvement over the common practice of using a lognormal model in which adequate EFH data are available to support maximum likelihood estimation.

Lognormal, gamma, Weibull, and generalized gamma distributions were fit to each factor data set using maximum likelihood estimation (Burmaster and Thompson, 1998). When sample sizes were available, the goodness of fit was calculated for each of the four models using the chi-square test (Bickel and Doksum, 1977). When percentile data were available but sample sizes were unknown, a regression F-test for the goodness of fit against the generalized gamma model was used. For each of the two-parameter models, parameter uncertainty information (i.e., mean, standard deviation, scale, and shape) was provided as parameter estimates for a bivariate normal distribution that could be used for simulating parameter values (Burmaster and Thompson, 1998). The information necessary for such simulations includes estimates of the two model parameters, their standard errors, and their correlation. To obtain this parameter uncertainty information, the asymptotic normality of the maximum likelihood estimate (Burmaster and Thompson, 1998) was used when sample sizes were available, and a regression approach was used when sample sizes were not available (Jennrich and Moore, 1975; Jennrich and Ralston, 1979). In either case, uncertainty can be expressed as a bivariate normal distribution for the model parameters.

The parameter values selected are described in more detail in the following subsections. **Section F.1.3** discusses fixed parameters. **Section F.1.4** describes, for each exposure factor, the EFH data used to develop the distributions, along with the final distributional statistics.

F.1.3 Fixed Parameters

Certain parameters were fixed, based on central tendency values from the best available source (usually EFH recommendations), either because no variability was expected or because the available data were not adequate to generate distributions. Fixed (constant) parameters are shown in **Table F-2** along with the value selected for the risk analysis and the data source. These constants included variables for which limited or no percentile data were provided in the EFH: exposure frequency, fractions of T3 and T4 fish consumed, and fraction contaminated for the various media. Most of these values were extracted directly from the EFH. When evaluating carcinogens, total dose was averaged over the lifetime of the individual, assumed to be 70 years.

[1] Gamma, Weibull, and lognormal distributions are all special cases of the generalized gamma distribution.

Table F-2. Summary of Human Exposure Factor Data Used in Modeling: Constants

Description	Value	Units	Source
Fraction contaminated: drinking water	1	Fraction	EPA policy
Fraction contaminated: fish	1	Fraction	EPA policy
Fraction of T3 fish consumed	0.36	Fraction	U.S. EPA (1997b); Table 10-66
Fraction of T4 fish consumed	0.64	Fraction	U.S. EPA (1997b); Table 10-66
Exposure frequency (adult, child)	350	d/yr	EPA policy
Averaging time for carcinogens (adult, child)	70	yr	U.S. EPA (1989)

The fraction contaminated for drinking water was assumed to be 1 (i.e., all drinking water available for consumption at a site is potentially contaminated), with actual concentrations depending on fate and transport model results. Thus, households for which the drinking water pathway was analyzed were assumed to get 100 percent of their drinking water from groundwater. Exposure frequency was set to 350 days per year in accordance with EPA policy, assuming that residents take an average of 2 weeks' vacation time away from their homes each year.

F.1.4 Variable Parameters

F.1.4.1 Fish Consumption

Table F-3 presents fish consumption data and distributions. Fish consumption data were obtained from Table 10-64 of the EFH (U.S. EPA, 1997b). Data (in g/d) were available for adult freshwater anglers in Maine. The Maine fish consumption study was one of four recommended freshwater angler studies in the EFH (U.S. EPA, 1997b). The other recommended fish consumption studies (i.e., Michigan and New York) had large percentages of anglers who fished from Great Lakes, which is not consistent with the modeling scenarios used in this risk analysis. The anglers in the Maine study fished from streams, rivers, and ponds; these data were more consistent with the CCW modeling scenarios. Although the Maine data have a lower mean than the Michigan data, the Maine data compared better with a national U.S. Department of Agriculture (USDA) study. Also, the Maine study included percentile data, which were necessary to develop a distribution.

Percentile data were used to fit parametric models (gamma, lognormal, and Weibull), and measures of goodness of fit were used to select lognormal as the most appropriate model. The fraction of fish intake that is locally caught was assumed to be 1 (in accordance with EPA policy). The fraction of consumed T3 and T4 fish was 0.36 and 0.64, respectively (Table 10-66, U.S. EPA, 1997b).

Table F-3. Fish Consumption Data and Distribution

EFH Data (g/d)									Distribution		
Age Cohort	N	Data Mean	Data SD	P50	P66	P75	P90	P95	Distribution	Pop-Estd Mean	Pop-Estd SD
All ages	1,053	6.4		2	4	5.8	13	26	Lognormal	6.48	19.9

N = Number of samples; P50–P95 = Percentiles; Pop-Estd = Population-estimated; SD = Standard deviation.

F.1.4.2 Drinking Water Intake

Table F-4 presents drinking water intake data and distributions. Drinking water intake data were obtained from Table 3-6 of the EFH (U.S. EPA, 1997a). Data (in mL/d) were presented by age groups. Weighted averages of percentiles, means, and standard deviations were calculated for the three child age groups and adults. Percentile data were used to fit parametric models (gamma, lognormal, and Weibull) using maximum likelihood estimation. Measures of goodness of fit were used to select the most appropriate model. The fraction of drinking water contaminated was assumed to be 1 (in accordance with EPA policy).

Table F-4. Drinking Water Intake Data and Distributions

EFH Data (mL/d)													Distributions		
Age Cohort	**N**	**Data Mean**	**Data SD**	**P01**	**P05**	**P10**	**P25**	**P50**	**P75**	**P90**	**P95**	**P99**	**Distribution**	**Pop-Estd Mean**	**Pop-Estd SD**
1–5	3,200	697.1	401.5	51.62	187.6	273.5	419.2	616.5	900.8	1,236	1,473	1,917	Gamma	698	406
6–11	2,405	787	417	68	241	318	484	731	1,016	1,338	1,556	1,998	Gamma	787	430
12–19	5,801	963.2	560.6	65.15	241.4	353.8	574.4	868.5	1,247	1,694	2,033	2,693	Gamma	965	574
20+	13,394	1,384	721.6	207.6	457.5	607.3	899.6	1,275	1,741	2,260	2,682	3,737	Gamma	1,383	703

N = Number of samples; P01–P99 = Percentiles; Pop-Estd = Population-estimated; SD = Standard deviation.

F.1.4.3 Body Weight

Table F-5 presents body weight data and distributions. Body weight data were obtained from Tables 7-2 through 7-7 of the EFH (U.S. EPA, 1997a). Data (in kg) were presented by age and gender. Weighted averages of percentiles, means, and standard deviations were calculated for 1- to 5-year-olds, 6- to 11-year-olds, 12- to 19-year olds, and adult age groups; male and female data were weighted and combined for each age group. These percentile data were used as the basis for fitting distributions. These data were analyzed to fit parametric models (gamma, lognormal, and Weibull) using maximum likelihood estimation. Measures of goodness of fit were used to select the most appropriate model.

Table F-5. Body Weight Data and Distributions

EFH Data (kg)													Distributions		
Age Cohort	**N**	**Data Mean**	**Data SD**	**P05**	**P10**	**P15**	**P25**	**P50**	**P75**	**P85**	**P90**	**P95**	**Distribution**	**Pop-Estd Mean**	**Pop-Estd SD**
1–5	3,762	15.52	3.719	12.5	13.1	13.45	14.03	15.26	16.67	17.58	18.32	19.45	Lognormal	15.5	2.05
6–11	1,725	30.84	9.561	22.79	24.05	25.07	26.44	29.58	33.44	36.82	39.66	43.5	Lognormal	30.7	5.96
12–19	2,615	58.45	13.64	43.84	46.52	48.31	50.94	56.77	63.57	68.09	71.98	79.52	Lognormal	58.2	10.2
20+	12,504	71.41	15.45	52.86	55.98	58.21	61.69	69.26	78.49	84.92	89.75	97.64	Lognormal	71.2	13.3

N = Number of samples; P05–P95 = Percentiles; Pop-Estd = Population-estimated; SD = Standard deviation.

F.1.4.4 Exposure Duration

Table F-6 presents exposure duration data and distributions. Exposure duration was assumed to be equivalent to the average residence time for each receptor. Exposure durations for adult and child residents were determined using data on residential occupancy from the EFH Table 15-168 (U.S. EPA, 1997c). The data represent the total time a person is expected to live at a single location, based on age. The table presents male and female data combined. Adult residents aged 21 to 90 were pooled. For child residents, the 3-year-old EFH age group was used for the 1- to 5-year-old CCW cohort. The 6- and 9-year-old EFH age groups were pooled for the 6- to 11-year-old CCW cohort.

Table F-6. Exposure Duration Data and Distributions

EFH Data		Distributions		
Age Cohort	**Data Mean (yr)**	**Distribution**	**Pop-Estd Shape (yr)[a]**	**Pop-Estd Scale (yr)**
1–5	6.5	Weibull	1.32	7.059
6–11	8.5	Weibull	1.69	9.467
Adult	16.0	Weibull	1.34	17.38

Pop-Estd = Population-estimated.
[a] Distributions used in risk assessment.

In an analysis of residential occupancy data, Myers et al. (U.S. EPA, 2000) found that the data, for most ages, were best fit by a Weibull distribution. The Weibull distribution as implemented in Crystal Ball is characterized by three parameters: location, shape, and scale. Location is the minimum value and, in this case, was presumed to be 0. Shape and scale were determined by fitting a Weibull distribution to the pooled data, as follows. To pool residential occupancy data for the age cohorts, an arithmetic mean of data means was calculated for each age group. Then, assuming a Weibull distribution, the variance within each age group (e.g., 6-year-olds) was calculated in the age cohort. These variances in turn were pooled over the age cohort using equal weights. This is not the usual type of pooled variance, which would exclude the variation in the group means. However, this way, the overall variance reflected the variance of means within the age groups (e.g., within the 6-year-old age group). The standard deviation was estimated as the square root of the variance. The coefficient of variation was calculated as the ratio of the standard deviation divided by the Weibull mean. For each cohort, the population-estimated parameter uncertainty information (e.g., shape and scale) was calculated based on a Weibull distribution, the calculated data mean for the age cohort, and the CV.

F.2 Exposure Parameters Used in Screening Analysis

The 50th percentile values used for the human exposure factors in the screening analysis are presented in **Table F-7**.

Table F-7. 50th Percentile Exposure Data Used in the Screening Analysis

Parameter	Value	Age Cohort				Units	Reference	Table
		1–5 yr	6–11 yr	12–19 yr	20+ yr			
Body weight		15.3	29.6	56.8	69.3	kg	U.S. EPA (1997a)	T7-2, 7-3, 7-4, 7-5, 7-6, 7-7
Consumption rate of fish		2	2	2	2	g WW/d	U.S. EPA (1997b)	T10-64
Exposure duration		5	7.5	8	10	yr	U.S. EPA (1997c)	T15-164, 15-168
Ingestion rate of drinking water		0.6165	0.731	0.8685	1.275	L/d	U.S. EPA (1997a)	T3-6

F.3 References

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Burmaster, D.E, and K.M. Thompson. 1998. Fitting second-order parametric distributions to data using maximum likelihood estimation. *Human and Ecological Risk Assessment 4*(2):319–339.

Jennrich, R.I., and R.H. Moore. 1975. Maximum likelihood estimation by nonlinear least squares. Pp. 57–65 in *Statistical Computing Section Proceedings of American Statistical Association*. American Statistical Association, Alexandria, VA.

Jennrich, R.I., and M.L. Ralston. 1979. Fitting nonlinear models to data. *Annual Review Biophysical Bioengineering 8*:195–238.

U.S. EPA (Environmental Protection Agency). 1989. *Risk Assessment Guidance for Superfund. Volume I: Human Health Evaluation Manual (Part A)* (Interim Final). EPA/540/1-89/002. Prepared by Office of Emergency and Remedial Response, Washington, DC. December.

U.S. EPA (Environmental Protection Agency). 1997a. *Exposure Factors Handbook, Volume I, General Factors.* EPA/600/P-95/002Fa. Office of Research and Development, Washington, DC. August.

U.S. EPA (Environmental Protection Agency). 1997b. *Exposure Factors Handbook, Volume II, Food Ingestion Factors.* EPA/600/P-95/002Fa. Office of Research and Development, Washington, DC. August.

U.S. EPA (Environmental Protection Agency). 1997c. *Exposure Factors Handbook, Volume III, Activity Factors.* EPA/600/P-95/002Fa. Office of Research and Development, Washington, DC. August.

U.S. EPA (Environmental Protection Agency). 1999. *Revised Risk Assessment for the Air Characteristic Study. Volume II: Technical Background Document*. EPA/530/R-99/019b. Office of Solid Waste, Washington, DC. August.

U.S. EPA (Environmental Protection Agency). 2000. *Options for Development of Parametric Probability Distributions for Exposure Factors.* EPA/600/R-00/058. National Center for Environmental Assessment, Office of Research and Development, Washington, DC. July.

Appendix G. Human Health Benchmarks

The CCW screening analysis and risk assessment require human health benchmarks to assess potential risks from chronic oral exposures. EPA uses reference doses (RfDs) to evaluate noncancer risk from oral exposures. Oral cancer slope factors (CSFs) are used to evaluate risk for carcinogens. This appendix provides the human health benchmarks used in the CCW screening and risk assessment. **Section G.1** describes the data sources and general hierarchy used to collect these benchmarks. **Section G.2** provides the benchmarks along with discussions of individual human health benchmarks extracted from a variety of sources.

G.1 Methodology and Data Sources

Several sources of health benchmarks are available. The hierarchy used health benchmarks developed by EPA to the extent that they were available. The analysis used available benchmarks from non-EPA sources for chemicals for which EPA benchmarks were not available, and ranked human health benchmark sources in the following order of preference:

- Integrated Risk Information System (IRIS)
- Superfund Technical Support Center Provisional Benchmarks
- Health Effects Assessment Summary Tables (HEAST)
- EPA health assessment documents
- Various other EPA health benchmark sources
- Agency for Toxic Substances and Disease Registry (ATSDR) minimal risk levels (MRLs)
- California Environmental Protection Agency (CalEPA) chronic inhalation reference exposure levels (RELs) and cancer potency factors.

G.1.1 Integrated Risk Information System (IRIS)

Benchmarks in IRIS are prepared and maintained by EPA, and RTI used values from IRIS whenever available. IRIS is EPA's electronic database containing information on human health effects (U.S. EPA, 2009). Each chemical file contains descriptive and quantitative information on potential health effects. Health benchmarks for chronic noncarcinogenic health effects include RfDs and inhalation reference concentrations (RfCs). Cancer classification, oral CSFs, and inhalation unit risk factors (URFs) are included for carcinogenic effects. IRIS is the official repository of Agency-wide consensus of human health risk information.

G.1.2 Superfund Provisional Benchmarks

The Superfund Technical Support Center (EPA's National Center for Environmental Assessment [NCEA]) derives provisional RfCs, RfDs, and CSFs for certain chemicals. Some of the provisional values have been externally peer reviewed. These provisional values have not undergone EPA's formal review process for finalizing benchmarks and do not represent Agency-wide consensus information.

G.1.3 Health Effects Assessment Summary Tables

HEAST is a listing of provisional noncarcinogenic and carcinogenic health toxicity values (RfDs, RfCs, URFs, and CSFs) derived by EPA (U.S. EPA, 1997). Although the health toxicity values in HEAST have undergone review and have the concurrence of individual EPA program offices, either they have not been reviewed as extensively as those in IRIS or their data set is not complete enough to be listed in IRIS. HEAST benchmarks have not been updated in several years and do not represent Agency-wide consensus information.

G.1.4 Other EPA Health Benchmarks

EPA has also derived health benchmark values in other risk assessment documents, such as Health Assessment Documents (HADs), Health Effects Assessments (HEAs), Health and Environmental Effects Profiles (HEEPs), Health and Environmental Effects Documents (HEEDs), Drinking Water Criteria Documents, and Ambient Water Quality Criteria Documents. Evaluations of potential carcinogenicity of chemicals in support of reportable quantity adjustments were published by EPA's Carcinogen Assessment Group (CAG) and may include cancer potency factor estimates. Health benchmarks derived by EPA for listing determinations (e.g., solvents) or studies (e.g., Air Characteristic Study) are also available. Health toxicity values identified in these EPA documents are usually dated and are not recognized as Agency-wide consensus information or verified benchmarks.

G.1.5 ATSDR Minimal Risk Levels

The ATSDR MRLs are substance-specific health guidance levels for noncarcinogenic endpoints (ATSDR, 2009). An MRL is an estimate of the daily human exposure to a hazardous substance that is likely to be without appreciable risk of adverse noncancer health effects over a specified duration of exposure. MRLs are based on noncancer health effects only and are not based on a consideration of cancer effects. MRLs are derived for acute, intermediate, and chronic exposure durations for oral and inhalation routes of exposure. Inhalation and oral MRLs are derived in a manner similar to EPA's RfCs and RfDs, respectively (i.e., ATSDR uses the no observed adverse effect level/uncertainty factor [NOAEL/UF] approach); however, MRLs are intended to serve as screening levels and are exposure duration specific. Also, ATSDR uses EPA's (U.S. EPA, 1994) inhalation dosimetry methodology in the derivation of inhalation MRLs.

G.1.6 CalEPA Cancer Potency Factors and Reference Exposure Levels

CalEPA has developed cancer potency factors for chemicals regulated under California's Hot Spots Air Toxics Program (CalEPA, 1999a). The cancer potency factors are analogous to EPA's oral and inhalation CSFs. CalEPA has also developed chronic inhalation RELs, analogous

to EPA's RfC, for 120 substances (CalEPA, 1999b, 2000, 2008). CalEPA used EPA's inhalation dosimetry methodology (U.S. EPA, 1994) in the derivation of inhalation RELs. The cancer potency factors and inhalation RELs have undergone internal peer review by various California agencies and have been the subject of public comment.

G.1.7 Surrogate Health Benchmarks

If no human health benchmarks were available from EPA or alternative sources, we sought benchmarks for similar chemicals to use as surrogate data. For example, the health benchmark of a mixture could serve as the surrogate benchmark for its components or a benchmark of a metal salt could serve as the surrogate for an elemental metal.

G.2 Human Health Benchmarks

The chronic human health benchmarks used to calculate the health-based numbers (HBNs) in the CCW screening analysis and risk assessment are summarized in **Table G-1**, which provides the Chemical Abstract Service Registry Number (CASRN), constituent name, RfD (mg/kg-d), oral CSF (mg/kg-d^{-1}), and reference for each benchmark. A key to the references cited and abbreviations used is provided at the end of the table.

For a majority of constituents, human health benchmarks were available from IRIS (U.S. EPA, 2009), Superfund Provisional Benchmarks, or HEAST (U.S. EPA, 1997). Benchmarks also were obtained from ATSDR (2009) or CalEPA (1999a, 1999b, 2000, 2008). This section describes benchmarks obtained from other sources, along with the Superfund Provisional Benchmarks values and special uses of IRIS benchmarks.

Table G-1. Human Health Benchmarks Used in CCW Risk Assessment

Constituent Name	CASRN	RfD (mg/kg-d)	Ref	CSFo (per mg/kg-d)	Ref	MCL (mg/L)	Notes
Aluminum	7429-90-5	1.0E+00	P				
Antimony	7440-36-0	4.0E-04	I				
Arsenic, inorganic	7440-38-2	3.0E-04	I	1.5E+0	I		
Barium	7440-39-3	2.0E-01	I				
Beryllium	7440-41-7	2.0E-03	I				
Boron	7440-42-8	2.0E-01	I				
Cadmium	7440-43-9	5.0E-04	I				RfD for H_2O (food = 1E-3)
Chloride	16887-00-6					250	
Chromium (III), insoluble salts	16065-83-1	1.5E+00	I				
Chromium (VI)	18540-29-9	3.0E-03	I				
Cobalt (and compounds)	7440-48-4	3.0E-04	P				
Copper	7440-50-8	1.0E-02	A			1.3	RfD is the intermediate oral MRL
Cyanide (amenable)	57-12-5	2.0E-02	I				

(continued)

Human Health Benchmarks Used in CCW Risk Assessment (continued)

Constituent Name	CASRN	RfD (mg/kg-d)	Ref	CSFo (per mg/kg-d)	Ref	MCL (mg/L)	Notes
Divalent mercury		3.0E-04	H				RfD is for mercuric chloride; used for food, water, soil
		1.0E-04	I				RfD is for methyl mercury; used for fish only
Fluoride	16984-48-8	1.2E-01	I				RfD is for fluorine; the alternative IRIS value (for skeletal, rather than dental, fluorosis) was used
Iron	7439-89-6	7.0E-01	P				
Lead and compounds (inorganic)	7439-92-1					0.015	
Manganese	7439-96-5	1.4E-01	I				RfD for food; H_2O and soil = 4.7E-2 mkd
Molybdenum	7439-98-7	5.0E-03	I				
Nickel, soluble salts	7440-02-0	2.0E-02	I				
Nitrate	14797-55-8	1.6E+00	I			10	
Nitrite	14797-65-0	1.0E-01	I				
Selenium	7782-49-2	5.0E-03	I				
Silver	7440-22-4	5.0E-03	I				
Strontium	7440-24-6	6.0E-01	I				
Sulfate	14808-79-8					250	
Thallium, elemental	7440-28-0	8.0E-05	I				RfD is for thallium chloride
Vanadium	7440-62-2	7.0E-03	H				
Zinc	7440-66-6	3.0E-01	I				

Key:
CASRN = Chemical Abstract Service registry number.
CSFo = Oral cancer slope factor.
RfD = Reference dose.
MCL = Maximum Contaminant Level.
Sources:
A = ATSDR MRLs (ATSDR, 2009)
H = HEAST (U.S. EPA, 1997)
I = IRIS (U.S. EPA, 2009)
P = PPRTV (U.S. EPA, 2006a, 2006b, 2008)

The provisional RfD of 1 mg/kg-d developed by NCEA for the Superfund Technical Support Center (U.S. EPA, 2006a) was used for aluminum.

The provisional RfD of 0.0003 mg/kg-d developed by NCEA for the Superfund Technical Support Center (U.S. EPA, 2008) was used for cobalt.

The provisional RfD of 0.7 mg/kg-d developed by NCEA for the Superfund Technical Support Center (U.S. EPA, 2006b) was used for iron.

For several constituents, IRIS benchmarks for similar chemicals were used as surrogate data. The rationale for these recommendations is as follows:

- Fluoride was based on fluorine. The IRIS RfD for fluorine is based on soluble fluoride. The primary RfD cited in IRIS (6E-02 mg/kg-d) is for dental fluorosis, a cosmetic effect. In this analysis, an alternative IRIS value (1.2E-01 mg/kg-d) for skeletal fluorosis in adults was used instead.

- Thallium was based on thallium chloride. IRIS contains RfDs for several thallium salts. The lowest value among the thallium salts (8E-05 mg/kg-d) is routinely used to represent thallium in risk assessments.

G.3 References

ATSDR (Agency for Toxic Substances and Disease Registry). 2009. *Minimal Risk Levels (MRLs) for Hazardous Substances.* Available at http://www.atsdr.cdc.gov/mrls.html.

CalEPA (California Environmental Protection Agency). 1999a. *Air Toxics Hot Spots Program Risk Assessment Guidelines: Part II. Technical Support Document for Describing Available Cancer Potency Factors*. Office of Environmental Health Hazard Assessment, Berkeley, CA. Available at http://www.oehha.org/air/cancer_guide/hsca2.html.

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U.S. EPA (Environmental Protection Agency). 1997. *Health Effects Assessment Summary Tables (HEAST)*. EPA-540-R-97-036. FY 1997 Update. Office of Solid Waste and Emergency Response, Washington, DC.

U.S. EPA (Environmental Protection Agency). 2006a. *Provisional Peer Reviewed Toxicity Values for Aluminum (CASRN 7429-90-5).* 10-23-2006. National Center for Environmental Assessment. Superfund Technical Support Center, Cincinnati, OH.

U.S. EPA (Environmental Protection Agency). 2006b. *Provisional Peer Reviewed Toxicity Values for Iron and Compounds (CASRN 7439-89-6). Derivation of Subchronic and Chronic Oral RfDs.* 9-11-2006. National Center for Environmental Assessment. Superfund Technical Support Center, Cincinnati, OH.

U.S. EPA (Environmental Protection Agency). 2008. *Provisional Peer Reviewed Toxicity Values for Cobalt (CASRN 7440-48-4).* 8-25-2008. National Center for Environmental Assessment. Superfund Technical Support Center, Cincinnati, OH.

U.S. EPA (Environmental Protection Agency). 2009. Integrated Risk Information System (IRIS). National Center for Environmental Assessment, Office of Research and Development, Washington, DC. Available at http://www.epa.gov/iris/.

Appendix H. Ecological Benchmarks

Both the screening and full-scale CCW assessments included an ecological risk assessment that paralleled the human health risk assessment. The ecological risk assessment addressed two routes of exposure for ecological receptors: direct contact with contaminated media and ingestion of contaminated food items. For each CCW chemical for which ecological effect data were available, hazard quotients (HQs) were calculated using chemical-specific media concentrations assumed to be protective of ecological receptors of concern.

This appendix provides the ecological benchmarks used in both the CCW screening and full-scale risk assessment. **Section H.1** describes the data sources and methods used to develop these benchmarks. Additional details can be found in U.S. EPA (1998). **Section H.2** provides the benchmarks.

H.1 Data Sources and Methodology

To calculate ecological HQs, the concentration-based ecological benchmarks (also known as chemical stressor concentration limits, or CSCLs) were divided by the estimated concentrations of constituents in environmental media contaminated by CCW. The CSCLs are environmental quality criteria intended to represent a protective threshold value for adverse effects to various ecological receptors in aquatic ecosystems (surface water and sediment). An HQ greater than target of 1 indicates that the predicted concentration will be above the CSCL and, therefore, the potential for adverse ecological effects exists. In this regard, the use of CSCLs to calculate an ecological HQ is analogous to the use of the reference concentration (RfC) for human health where the air concentration is compared to the health-based concentration (the RfC), and an HQ greater than the target value of 1 is considered to indicate the potential for adverse health effects. **Table H-1** shows the receptor types assessed for each exposure route in each environmental medium addressed by the CCW risk assessment.

Table H-1. Ecological Receptors Assessed by Medium Impacted by CCW

Receptor Type	Surface Water	Sediment
Direct Contact Exposure		
Aquatic Community	✔	
Sediment Community		✔
Amphibians	✔	
Aquatic Plants and Algae	✔	
Ingestion Exposure		
Mammals	✔	
Birds	✔	

Ecological benchmarks for the CCW risk assessment were taken directly from the 1998 fossil fuel combustion risk analysis, *Non-Groundwater Pathways, Human Health and Ecological*

Risk Analysis for Fossil Fuel Combustion Phase 2 (FFC2) (U.S. EPA, 1998). The receptors and endpoints selected for the 1998 analysis were evaluated and considered appropriate for the goals of this risk assessment. The benchmarks were derived for each chemical and receptor to the extent that supporting data were available.

As in 1998, the lowest (most sensitive) benchmark for each chemical in each medium was selected to calculate HQs in the CCW risk assessment. For example, several receptors (aquatic invertebrates, mammals, and birds) may be exposed to constituents in surface water. The surface water HQ for a given chemical was calculated using whichever benchmark was lowest and would thus give the highest (most protective) HQ.

H.1.1 Direct Contact Exposure

Ecological receptors that live in close contact with contaminated media are considered to be potentially at risk. These receptors are exposed through direct contact with contaminants in surface water and sediment. The receptors selected to assess the direct contact exposure route for each medium are summarized in Table H-1. The benchmarks for receptor communities are not truly *community-level* concentration limits in that they do not consider predator-prey interactions. Rather, they are based on the theory that protection of 95 percent of the species in the community will provide a sufficient level of protection for the community (see, for example, Stephan et al., 1985, for additional detail). The following sections summarize the benchmark derivation methods for each receptor assessed for the direct contact route of exposure.

Aquatic Community Benchmarks

The aquatic community receptor comprises fish and aquatic invertebrates exposed through direct contact with constituents in surface water. For the aquatic community, the final chronic value (FCV), developed either for the Great Lakes Water Quality Initiative (U.S. EPA, 1993) or the National Ambient Water Quality Criteria (NAWQC) (U.S. EPA, 1995a,b), was the preferred source for the benchmark. If an FCV was unavailable and could not be calculated from available data, a secondary chronic value (SCV) was estimated using methods developed for wildlife criteria for the Great Lakes Initiative (e.g., 58 FR 20802; U.S. EPA, 1993). The SCV methodology is based on the original species data set established for the NAWQC; however, it requires fewer data points and includes statistically derived adjustment factors. For benchmark derivation, the minimum data set required at least one data point.

Amphibian Benchmarks

For amphibian populations, data availability severely limited benchmark development. A review of several compendia presenting amphibian ecotoxicity data (e.g., U.S. EPA, 1996; Power et al., 1989), as well as primary literature sources, found a lack of standard methods on endpoints, species, and test durations necessary to derive a chronic benchmark for amphibians. Consequently, an acute benchmark was derived for aqueous exposures in amphibians by taking a geometric mean of LC_{50} (i.e., concentration lethal to 50 percent of test subjects) data identified in studies with exposure durations less than 8 days. Although the use of acute effects levels produced a benchmark that was not consistent with the other (chronic) ecological benchmarks, the sensitivity of these receptors warranted the use of acute effects levels in the absence of chronic concentration limits. Recent studies (Hopkins and Rowe, 2004; Hopkins et al., 2006)

have confirmed that amphibians are among the most sensitive taxa to metals found in CCW, and selenium appears to be a significant stressor in CCW disposal scenarios. The endpoints considered in these studies were related to population sustainability and, consequently, are highly relevant to ecological risk assessment. However, these field studies were confounded by the fact that wildlife were exposed to multiple chemical pollutants (including radionuclides) and, as a result, acute effects data on individual metals remain the most appropriate source for quantitative benchmarks to assess the potential for adverse effects in amphibians.

Sediment Community Benchmarks

For the sediment community, benchmarks were selected based on a complete assessment of several sources proposing sediment benchmark values. Primary sources evaluated for developing sediment community benchmarks are shown in **Table H-2**.

Table H-2. Primary Sources Evaluated for Developing Sediment Community Benchmarks

Long, E.R., and L.G. Morgan. 1991. *The Potential for Biological Effects of Sediment-Sorbed Contaminants Tested in the National Status and Trends Program*. Technical Memorandum NOS OMA 52. National Oceanic and Atmospheric Administration (NOAA), Washington, DC.
Jones, D.S., G.W. Suter, II, and R.N. Hull. 1997. *Toxicological Benchmarks for Screening Contaminants of Potential Concern for Effects on Sediment-Associated Biota: 1997 Revision*. Oak Ridge National Laboratory, Oak Ridge, TN.
U.S. EPA (Environmental Protection Agency). 1997. *Protocol for Screening Level Ecological Risk Assessment at Hazardous Waste Combustion Facilities*. Internal Review Draft, February 28. Office of Solid Waste, Washington, DC.
U.S. EPA (Environmental Protection Agency). 1995. *Technical Support Document for the Hazardous Waste Identification Rule: Risk Assessment for Human and Ecological Receptors*. Office of Solid Waste, Washington, DC.
MacDonald, D.D. 1994. *Approach to the Assessment of Sediment Quality in Florida Coastal Waters. Volume 1*. Florida Department of Environmental Protection, Tallahassee, FL.

Algae and Aquatic Plant Benchmarks

For algae and aquatic plants, adverse effects concentrations were identified in the open literature or from a data compilation presented in *Toxicological Benchmarks for Screening Potential Contaminants of Concern for Effects on Aquatic Biota: 1996 Revision* (Suter and Tsao, 1996). For most contaminants, studies were not available for aquatic vascular plants, and lowest effects concentrations were identified for algae. The benchmark for algae and aquatic plants was based on (1) an LOEC for vascular aquatic plants or (2) an effective concentration (EC_{xx}) for a species of freshwater algae, frequently a species of green algae (e.g., *Selenastrum capricornutum*). Because of the lack of data for this receptor group and the differences between vascular aquatic plants and algae sensitivity, the lowest value of those identified was usually chosen.

H.1.2 Ingestion Exposure

The ingestion route of exposure addresses the exposure of terrestrial mammals and birds through ingestion of aquatic plants and prey. Thus, the CCW ecological benchmarks for ingestion exposure express media concentrations that, based on certain assumptions about receptor diet and foraging behavior, were expected to be protective of populations of mammals and birds feeding and foraging in contaminated surface water bodies.

The derivation of ingestion benchmarks began with the selection of appropriate ecotoxicological data based on a hierarchy of data sources. The assessment endpoint for the CCW ecological risk assessment was population viability; therefore, ecological benchmarks were developed from measures of reproductive/developmental success or, if unavailable, from other effects that could conceivably impair population dynamics. Population-level benchmarks were preferred over benchmarks for individual organisms; however, very few population-level benchmarks have been developed. Therefore, the CCW risk assessment used benchmarks derived from individual organism studies, and protection was inferred at the population level.

Once an appropriate ingestion exposure study was identified, a benchmark was calculated using a three-step process. The remainder of this section outlines the basic technical approach used to convert avian or mammalian benchmarks (in daily doses) to the media concentration benchmarks (in units of concentration) used to assess ecological risks for surface water and sediment contaminated by CCW waste constituents. The methods reflect exposure through the ingestion of contaminated plants, prey, and media, and include parameters on accumulation (e.g., bioconcentration factors), uptake (e.g., consumption rates), and dietary preferences.

Step 1: Scale Benchmark

The benchmarks derived for test species can be extrapolated to wildlife receptor species within the same taxon using a cross-species scaling equation (Equation H-1) (Sample et al., 1996). This is the default methodology EPA proposed for carcinogenicity assessments and reportable quantity documents for adjusting animal data to an equivalent human dose (57 FR 24152).

$$Benchmark_w = LOAEL_t \times \left(\frac{bw_t}{bw_w}\right)^{1/4} \qquad \text{(H-1)}$$

where

$Benchmark_w$ = scaled ecological benchmark for species *w* (mg/kg/d)
$LOAEL_t$ = lowest observed adverse effects level for test species (mg/kg/d)
bw_t = body weight of the surrogate test species (kg)
bw_w = body weight of the representative wildlife species (kg).

Step 2: Identify Bioconcentration Factors/Bioaccumulation Factors

For metal constituents, whole-body bioconcentration factors (BCFs) and bioaccumulation factors (BAFs) were identified for aquatic organisms that could be used as food sources (e.g., fish). The Oak Ridge National Laboratory has proposed methods and data that are useful in predicting bioaccumulation (Sample et al. 1998a,b). These values were typically identified in the open literature and EPA references.

Step 3: Calculate Benchmarks

The following equation provided the basis for calculating surface water benchmarks using a population-inference benchmark (e.g., endpoint on fecundity).

$$Benchmark = \frac{\left[I_{fish} \times \left(BAF \quad C_w\right)\right] + \left(I_w \times C_w\right)}{bw} \tag{H-2}$$

where

I_{fish}	=	intake of contaminated fish (kg/d)
BAF	=	whole-body bioaccumulation factor (L/kg)
bw	=	weight of the representative species (kg)
I_w	=	intake of contaminated water (L/d)
C_w	=	total concentration in the water (mg/L).

For chemicals that bioaccumulate significantly in fish tissue, the ingestion of contaminated food tends to dominate the exposure (i.e., $[I_{fish} \times C_{fish}] >> [I_w\ C_w]$), and the water term (i.e., $[I_w \times C_w]$) can be dropped from Equation H-2, resulting in Equation H-3:

$$Benchmark = \frac{I_{fish} \times \left(BAF \times C_w\right)}{bw} \tag{H-3}$$

At the benchmark dose (mg/kg/d), the concentration in water is equivalent to the chemical stressor concentration limit for that receptor as a function of body weight, ingestion rate, and the bioaccumulation potential for the chemical of concern. Hence, Equation H-3 can be rewritten to solve for the surface water ($CSCL_{sw}$) as follows:

$$CSCL_{sw} = \frac{benchmark \times bw}{I_w + \left(I_{fish} \times BAF\right)} \tag{H-4}$$

H.2 Ecological Benchmarks

The ecological benchmarks used to calculate ecological HQs in the CCW risk assessment are summarized in **Table H-3**, which provides the constituent name; the criterion and receptor for sediment and aquatic receptors; and the source for each benchmark.

Table H-3. Ecological Benchmarks Used in the CCW Risk Assessment

Constituent	Sediment Criterion (mg/kg)	Sediment Receptor	Aquatic Criterion (mg/L)	Aquatic Receptor	Source
Aluminum	ID	--	0.09	Aquatic Biota	U.S. EPA (1998)
Antimony	2	Sediment biota	0.03	Aquatic Biota	U.S. EPA (1998)
Arsenic total	0.51	Spotted sandpiper	ID	--	U.S. EPA (1998)
Arsenic III	ID	--	0.15	Aquatic Biota	U.S. EPA (1998)
Arsenic IV	ID	--	8.10E-03	Aquatic Biota	U.S. EPA (1998)
Barium	190	Spotted sandpiper	4.00E-03	Aquatic Biota	U.S. EPA (1998)
Beryllium	ID	--	6.60E-04	Aquatic Biota	U.S. EPA (1998)
Boron	ID	--	1.60E-03	Aquatic Biota	U.S. EPA (1998)
Cadmium	0.68	Sediment biota	2.50E-03	Aquatic Biota	U.S. EPA (1998)
Chromium total	16.63	Spotted sandpiper	ID	--	U.S. EPA (1998)
Chromium IV	ID	--	0.09	Aquatic Biota	U.S. EPA (1998)
Chromium VI	ID	--	0.01	Aquatic Biota	U.S. EPA (1998)
Cobalt	ID	--	0.02	Aquatic Biota	U.S. EPA (1998)
Copper	18.7	Sediment biota	9.30E-03	Aquatic Biota	U.S. EPA (1998)
Lead	0.22	Spotted sandpiper	3.00E-04	River Otter	U.S. EPA (1998)
Mercury	0.11	Spotted sandpiper	1.90E-07	Kingfisher	U.S. EPA (1998)
Molybdenum	34	Spotted sandpiper	0.37	Aquatic Biota	U.S. EPA (1998)
Nickel	15.9	Sediment biota	0.05	Aquatic Biota	U.S. EPA (1998)
Selenium total	ID	--	5.00E-03	Aquatic Biota	U.S. EPA (1998)
Selenium IV	ID	--	0.03	Aquatic Biota	U.S. EPA (1998)
Selenium VI	ID	--	9.50E-03	Aquatic Biota	U.S. EPA (1998)
Silver	0.73	Sediment biota	3.60E-04	Aquatic Biota	U.S. EPA (1998)
Thallium	ID	--	0.01	Aquatic Biota	U.S. EPA (1998)
Vanadium	18	Spotted sandpiper	0.02	Aquatic Biota	U.S. EPA (1998)
Zinc	120	Sediment biota	0.12	Aquatic Biota	U.S. EPA (1998)

ID = insufficient data.

H.3 References

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Appendix I. Calculation of Health-Based Numbers (HBNs) for CCW Constituent Screening

Management of CCW can result in contaminants moving from a waste management unit (WMU) and contaminating groundwater, and surface water via groundwater transport from a CCW WMU. Under these scenarios, individuals living near WMUs may then come into contact with chemicals via ingestion of contaminated drinking water or ingestion of fish contaminated via chemical uptake and accumulation.

Key Features of HBN Calculations

- HBNs calculated for groundwater (mg/L) and surface water (mg/L)
- HBNs based on a target cancer risk of 10^{-5} and a HQ of 1
- Groundwater HBNs based on a residential drinking water scenario
- Surface water HBNs based on a recreational fisher scenario
- Adult and child receptors first exposed at ages 3, 8, 15 and 20
- Exposure factors set at central tendency values
- Source size set at the 95th percentile of CCW landfills.

Health-based numbers (HBNs) for groundwater (as drinking water) and surface water were used in this analysis to consider risks and hazards to human receptors from chemicals that are released from CCW management units and move through the subsurface. HBNs represent concentrations in environmental media that will not cause an exceedance of a target cancer risk of 10^{-5} or a hazard quotient (HQ) of 1.

The pathways included in the HBN calculations are summarized in **Table I-1**. The HBN for groundwater was based on domestic use of groundwater as drinking water. Surface water HBNs were based on a recreational fisher scenario in which the receptor was assumed to live at a different off-site location and to be exposed only to fish caught recreationally.

Table I-1. Pathways Included in HBN Calculations

HBN Calculation	Drinking Water Ingestion	Fish Ingestion
Groundwater HBN	✓	
Surface water HBN		✓

I.1 Methodology

All HBNs considered human receptors exposed to contaminated media and/or food items at different ages to take into account changing exposure patterns with age. The specific receptors considered were individuals exposed starting at ages 3, 8, 15, and 20. Depending on the start age, an appropriate exposure duration was selected for each receptor based on residency data. Each receptor was exposed for the period of time determined by the exposure duration, and the model accounted for changes in exposure patterns as a person ages. All exposure parameters selected for this analysis were based on 50th percentile values. Once the cancer risks and HQs were calculated for each receptor, HBNs were calculated based on total cancer risk, noncancer inhalation, and noncancer ingestion. The most protective HBN (i.e., the lowest across all age

groups) was selected. In all cases, the HBN calculations used central tendency exposure factors (e.g., body weight, exposure duration, exposure frequency, consumption rates).

The equations used to calculate the HBNs are provided at the end of this appendix; **Table I-2** lists the tables of equations by exposure pathway (**Tables I-4** through **I-8**). Data used in these equations to calculate the CCW HBNs can be found in the other appendices to this report, as well as in **Table I-9**, which provides the age cohort–specific human exposure factors used in the HBN calculations.

Table I-2. Key to Tables of Equations Used to Calculate HBNs

Equation for Fish Concentrations	
I-4	Concentration in Fish at Different Trophic Levels (mg/kg)
Equations for Human Exposure	
I-5	Daily Intake of Contaminant from Consumption of Fish (mg/kg BW/day)
I-6	Daily Intake of Contaminant from Consumption of Drinking Water (mg/kg BW/day)
Equations for Unit Risk Calculations and Health-based Numbers	
I-7	Cancer Risk and Hazard Quotient Due to Ingestion (unitless)
I-8	Health-Based Concentration (mg/L)

Groundwater HBNs were based on standard residential exposure assumptions for drinking water consumption, using equations from (U.S. EPA, 1998a). The surface water HBNs were based on concentrations in fish estimated using an aquatic food chain model; that methodology is described in the rest of this section.

The methodology used for estimating concentrations in fish was based on EPA's *Methodology for Assessing Health Risks Associated with Multiple Pathways of Exposure to Combustor Emissions* (U.S. EPA, 1998a). An aquatic food chain model was used to estimate the concentration of constituent that may accumulate in fish. It was assumed for this analysis that fish are a food source for a recreational fisher. Trophic level three (T3) and four (T4) fish were considered in this analysis. T3 fish are those that consume invertebrates and plankton. T4 fish are those that consume other fish. Most of the fish that humans eat are T4 fish (e.g., salmon, trout, walleye, bass) and medium to large T3 fish (e.g., carp, smelt, perch, catfish, sucker, bullhead, sauger). For metals other than mercury, the calculation of contaminants in fish was based on the total concentration of contaminants in the waterbody (i.e., dissolved and suspended solids). For mercury, the calculation of contaminants in fish was based on the dissolved concentration of methyl mercury in the waterbody.

Fish tissue concentrations are dependent on a bioconcentration factor (BCF), which is used to estimate the amount of constituent being transferred from the waterbody into the fish tissue. Specifically, BCFs reflect the ratio between the tissue concentration in fish and the appropriate waterbody concentration. BCFs were developed for each constituent to reflect accumulation in each trophic level considered. They were also developed to estimate the concentration in the fish filet versus the total fish. Human receptors consume only the filet portion of the fish, which has a lower lipid content. Because some constituents tend to accumulate in the fatty tissue, the concentration in the filet portion of the fish is sometimes lower than the concentration in the whole fish.

I.2 Health-Based Numbers

Table I-3 provides the HBNs for surface water and groundwater.

Table I-3. Groundwater and Surface Water HBNs

Chemical	Benchmark Type	Groundwater HBN (mg/L)[1]	Surface Water HBN[2] (mg/L)
Aluminum	Noncancer	29.4	NA
Antimony	Noncancer	0.012	NA
Arsenic	Cancer	0.0029	0.23
Arsenic	Noncancer	0.0088	0.71
Barium	Noncancer	5.89	NA
Beryllium	Noncancer	0.059	1.0
Boron	Noncancer	5.87	NA
Cadmium	Noncancer	0.015	0.035
Chromium (III)	Noncancer	44	23,700
Chromium (VI)	Noncancer	0.088	47
Cobalt	Noncancer	0.0088	NA
Copper[3]	Noncancer (GW)/AWQ (SW)	0.29	1.3
Cyanide	Noncancer	0.59	NA
Fluoride	Noncancer	3.52	NA
Lead	MCL	0.015	NA
Manganese	Noncancer	1.4	NA
Mercury	Noncancer	0.0088	3.85E-06
Molybdenum	Noncancer	0.147	12
Nickel	Noncancer	0.59	237
Nitrate	MCL	10	NA
Nitrate	Noncancer	47	NA
Nitrite	Noncancer	2.9	NA
Selenium	Noncancer	0.147	0.038
Silver	Noncancer	0.147	NA
Strontium	Noncancer	17.6	NA
Thallium	Noncancer	0.0024	0.008
Vanadium	Noncancer	0.21	NA
Zinc	Noncancer	8.8	8.13

[1] Based on domestic drinking water ingestion.
[2] Based on fish consumption by a recreational fisher.
[3] Fish bioconcentration factor values for copper are zero. HBN based on National Ambient Water Quality Criteria.
AWQ = National Ambient Water Quality Criteria
MCL = maximum contaminant level or drinking water action level (for lead and copper)
NA = not available

Table I-4. Concentration in Fish at Different Trophic Levels (mg/kg)

Cfish_T

For Mercury:

$$Cfish_T = Cdiss \times BCF_T$$

$$Cdiss = 0.05 \times Cwt$$

For NonvolatileMetals:

$$Cfish_T = Cwt \times BCF_T$$

Name	Description	Value
Cdiss	Concentration in surface water (dissolved) (mg/L)	Calculated
Cwt	Concentration in surface water (total) (mg/L)	Set equal to 1 for HBN calculation
0.05	Fraction of total mercury as dissolved methyl mercury	Derived from U.S. EPA, 1997a
BCF_T3F	Bioconcentration factor for trophic level 3, fish filet (L/kg)	Chemical-specific (see App. J)
BCF_T3W	Bioconcentration factor for trophic level 3, fish whole (L/kg)	Chemical-specific (see App. J)
BCF_T4F	Bioconcentration factor for trophic level 4, fish filet (L/kg)	Chemical-specific (see App. J)
BCF_T4W	Bioconcentration factor for trophic level 4, fish whole (L/kg)	Chemical-specific (see App. J)

Source: U.S. EPA, 1998a.

Table I-5. Daily Intake of Contaminant from Consumption of Fish (mg/kg BW/day)

Ifish

$$Cfish_T = F_{T3} \times C_{fishT3F} + F_{T4} \times C_{fishT4F}$$

$$Ifish = Cfish_T \times CR_{fish} \times \frac{F_{fish}}{1{,}000 \times BW}$$

Name	Description	Value
1000	Conversion factor (g/kg)	
C_fishT3F	Concentration of contaminant in fish at different trophic levels (mg/kg)	Calculated (Table I-4)
C_fishT4F	Concentration of contaminant in fish at different trophic levels (mg/kg)	Calculated (Table I-4)
$Cfish_T$	Concentration of contaminant in fish (mg/kg)	Calculated (Table I-4)
BW	Body weight (kg)	Age-cohort-specific (Table I-9)
CR_fish	Consumption rate of fish (g WW/day)	Age-cohort-specific (Table I-9)
F_fish	Fraction of fish intake from contaminated source (unitless)	1 (protective value)
F_T3	Fraction of trophic level 3 intake (unitless)	0.36 (U.S. EPA, 1997d)
F_T4	Fraction of trophic level 4 intake (unitless)	0.64 (U.S. EPA, 1997d)

Source: U.S. EPA, 1998a.

Table I-6. Daily Intake of Contaminant from Consumption of Drinking Water (mg/kg BW/day)

Idw

$$Idw = C_{dw} \times Cr_{dw} \times \frac{F_{dw}}{BW}$$

Name	Description	Value
1000	Conversion factor (mL/L)	
Cdw	Concentration of contaminant in drinking water (mg/L)	Set equal to 1 for HBN calculation
BW	Body weight (kg)	Age-cohort-specific (Table I-9)
CR_dw	Consumption rate of water (L/day)	Age-cohort-specific (Table I-9)
F_dw	Fraction of drinking water ingested that is contaminated (unitless)	1 (protective value)

Source: U.S. EPA, 1998a.

Table I-7. Cancer Risk and Hazard Quotient Due to Ingestion (unitless)

Risk_Oral

$$HQ_{Oral} = \frac{I}{RfD}$$

$$Risk_{Oral} = \frac{I \times ED \times EF \times CSF_{Oral}}{AT \times 365}$$

Name	Description	Value
365	Conversion factor (days/yr)	
I	Intake rate from fish or drinking water (mg/kg/day)	Calculated (Tables I-5 and I-6)
CSF_{Oral}	Oral cancer slope factor (mg/kg/day)-1	Chemical-specific (see Appendix G)
RfD	Noncancer reference dose (mg/kg/day)	Chemical-specific (see Appendix G)
AT	Averaging time (yr)	70 (U.S. EPA, 1991)
ED	Exposure duration for oral ingestion (yr)	Age-cohort-specific (Table I-9)
EF	Exposure frequency (days/yr)	350 (U.S. EPA, 1991)

Table I-8. Health-Based Concentration (ppm)

CalcHBN

$$HBN_{NC_{Oral}} = \frac{C}{HQ_{Oral}} \times THQ$$

$$HBN_{Risk} = \frac{C}{Risk} \times TR$$

Name	Description	Value
THQ	Target noncancer hazard quotient (unitless)	1
TR	Target cancer risk (unitless)	1.00E-5
HQ_Oral	Noncancer hazard quotient for ingestion (unitless)	Calculated (Table I-7)
Risk	Total cancer risk (unitless)	Calculated (Table I-7)
C	Constituent concentration in media (mg/L or mg/kg)	Value set to unit concentration of 1

Back calculation assuming linearity.

Table I-9. Age Cohort-Specific Human Exposure Factors

Parameter	Cohort_1	Cohort_2	Cohort_3	Cohort_4
Body weight (BW) (kg)	15.3	29.6	56.8	69.3
Start year (SY) (yr)	3	8	15	20
Fish consumption rate (CR_fish) (g WW/day)	2	2	2	2
Exposure duration (ED) (yr)	5	7.5	8	10
Drinking water consumption rate (CR_dw) (L/day)	0.6165	0.731	0.8685	1.275

I.3 References

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Appendix J. Chemical-Specific Inputs Used in CCW Constituent Screening

Chemical-specific inputs used to develop the CCW HBNs include the bioconcentration factors needed to estimate exposure concentrations in fish. Values for these inputs are obtained from the best available literature source. **Table J-1** provides, for each chemical in the CCW screening analysis, the values used in the analysis along with the source of each value.

Table J-1. Fish Bioconcentration Factors

Parameter[a]	Value (L/kg)	Reference	Comment
Aluminum (7429905)			
No Data			
Antimony (7440360)			
BCF_T3F	0	Barrows et al. (1980)	BCF_T3W was used as a surrogate.
BCF_T3W	0	Barrows et al. (1980)	Species was sunfish.
BCF_T4F	0	Barrows et al. (1980)	BCF_T3W was used as a surrogate.
BCF_T4W	0	Barrows et al. (1980)	BCF_T3W was used as a surrogate.
Arsenic (7440382)			
BCF_T3F	4	Barrows et al. (1980)	BCF_T3W was used as a surrogate.
BCF_T3W	4	Barrows et al. (1980)	Species was sunfish.
BCF_T4F	4	Barrows et al. (1980)	BCF_T3W was used as a surrogate.
BCF_T4W	4	Barrows et al. (1980)	BCF_T3W was used as a surrogate.
Barium (7440393)			
No Data			
Beryllium (7440417)			
BCF_T3F	19	Barrows et al. (1980)	BCF_T3W was used as a surrogate.
BCF_T3W	19	Barrows et al. (1980)	Species was sunfish.
BCF_T4F	19	Barrows et al. (1980)	BCF_T3W was used as a surrogate.
BCF_T4W	19	Barrows et al. (1980)	BCF_T3W was used as a surrogate.
Boron (7440428)			
No Data			
Cadmium (7440439)			
BCF_T3F	270	Kumada et al. (1972)	BCF_T3W was used as a surrogate.
BCF_T3W	270	Kumada et al. (1972)	Geomean of 3 data points in Table 2.
BCF_T4F	270	Kumada et al. (1972)	BCF_T4W was used as a surrogate.
BCF_T4W	270	Kumada et al. (1972)	Geomean of 3 data points in Table 2. Species were doce and rainbow trout.

(continued)

Fish Bioconcentration Factors (continued)

Parameter[a]	Value (L/kg)	Reference	Comment
Chromium(III) (16065831)			
BCF_T3F	0.6	Stephan (1993)	BCF_T4F was used as a surrogate.
BCF_T3W	0.6	Stephan (1993)	BCF_T4F was used as a surrogate.
BCF_T4F	0.6	Stephan (1993)	Geomean (as cited in Stephan, 1993) based on Buhler et al. (1977) and Calamari et al. (1982). Used chromium as a surrogate.
BCF_T4W	0.6	Stephan (1993)	BCF_T4F was used as a surrogate.
Chromium(VI) (18540299)			
BCF_T3F	0.6	Stephan (1993)	BCF_T4F was used as a surrogate.
BCF_T3W	0.6	Stephan (1993)	BCF_T4F was used as a surrogate.
BCF_T4F	0.6	Stephan (1993)	Geomean (as cited in Stephan, 1993) based on Buhler et al. (1977) and Calamari et al. (1982). Used chromium as a surrogate.
BCF_T4W	0.6	Stephan (1993)	BCF_T4F was used as a surrogate.
Copper (7440508)			
BCF_T3F	0	Stephan (1993)	
BCF_T3W	0	Stephan (1993)	
BCF_T4F	0	Stephan (1993)	
BCF_T4W	0	Stephan (1993)	
Cobalt (7440484)			
No Data			
Cyanide (57125)			
No Data			
Fluoride (16984488)			
No Data			
Manganese (7439965)			
No Data			
Molybdenum (7439987)			
BCF_T3F	4	Eisler (1989)	BCF_T4F was used as a surrogate.
BCF_T3W	4	Eisler (1989)	BCF_T4F was used as a surrogate.
BCF_T4F	4	Eisler (1989)	Geomean of values found on pages 27 and 28. Species were rainbow trout and steelhead trout.
BCF_T4W	4	Eisler (1989)	BCF_T4F was used as a surrogate.
Nickel (7440020)			
BCF_T3F	0.8	Stephan (1993)	BCF_T4F was used as a surrogate.
BCF_T3W	0.8	Stephan (1993)	BCF_T4F was used as a surrogate.
BCF_T4F	0.8	Stephan (1993)	Derived from Calamari et al. (1982) (as cited in Stephan, 1993).
BCF_T4W	0.8	Stephan (1993)	BCF_T4F was used as a surrogate.

(continued)

Fish Bioconcentration Factors (continued)

Parameter[a]	Value (L/kg)	Reference	Comment
Selenium (7782492)			
BCF_T3F	490	Lemly (1985)	Based on threadfin shad and blueback herring. Units corrected.
BCF_T3W	490	Lemly (1985)	BCF_T3F was used as a surrogate.
BCF_T4F	1,700	Lemly (1985)	Based on threadfin shad and blueback herring. Units corrected.
BCF_T4W	1,700	Lemly (1985)	BCF_T4F was used as a surrogate.
Silver (7440224)			
BCF_T3F	0	Barrows et al. (1980)	BCF_T3W was used as a surrogate.
BCF_T3W	0	Barrows et al. (1980)	Species was sunfish.
BCF_T4F	0	Barrows et al. (1980)	BCF_T3W was used as a surrogate.
BCF_T4W	0	Barrows et al. (1980)	BCF_T3W was used as a surrogate.
Strontium (7440246)			
No Data			
Thallium (7440280)			
BCF_T3F	34	Barrows et al. (1980)	BCF_T3W was used as a surrogate.
BCF_T3W	34	Barrows et al. (1980)	Species was sunfish.
BCF_T4F	130	Stephan (1993)	Derived from Zitko et al. (1975) (as cited in Stephan, 1993).
BCF_T4W	130	Stephan (1993)	BCF_T4F was used as a surrogate.
Total Nitrate Nitrogen (14797558)			
No Data			
Vanadium (7440622)			
No Data			
Zinc (7440666)			
BCF_T3F	350	Murphy et al. (1978)	BCF_T3W was used as a surrogate.
BCF_T3W	350	Murphy et al. (1978)	Geomean of converted dry weight concentration in Table 1 of bluegills at Site A and B.
BCF_T4F	350	Murphy et al. (1978)	BCF_T3W was used as a surrogate.
BCF_T4W	350	Murphy et al. (1978)	BCF_T3W was used as a surrogate.

[a] BCF_T3F = Bioconcentration factor for trophic level 3 fish, filet
BCF_T3W = Bioconcentration factor for trophic level 3 fish, whole
BCF_T4F = Bioconcentration factor for trophic level 4 fish, filet
BCF_T4W = Bioconcentration factor for trophic level 4 fish, whole

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Appendix K. Screening Analysis Results

Table K-1. CCW Surface Impoundment (SI) Human Health Screening Results: Groundwater-to-Drinking-Water Pathway

Chemical	Benchmark Type	HBN (mg/L)	2002 SI Porewater	
			90th Percentile	HQ(Cancer Risk)
Analytes Exceeding Risk Criteria[1]				
Antimony	Noncancer	1.17E-02	6.40E-02	5.45E+00
Arsenic	Cancer	2.86E-03	5.18E+00	(1.81E-02)
Arsenic	Noncancer	8.81E-03	5.18E+00	5.88E+02
Boron	Noncancer	5.87E+00	7.52E+01	1.28E+01
Cadmium	Noncancer	1.47E-02	1.31E-01	8.91E+00
Chromium (VI)	Noncancer	8.81E-02	3.66E-01	4.15E+00
Cobalt	Noncancer	8.81E-03	6.27E+00	7.13E+02
Fluoride	Noncancer	3.52E+00	1.91E+01	5.42E+00
Lead	MCL	1.50E-02	1.77E-01	1.18E+01
Manganese	Noncancer	1.38E+00	7.67E+00	5.56E+00
Molybdenum	Noncancer	1.47E-01	1.00E+00	6.81E+00
Nickel	Noncancer	5.87E-01	7.49E-01	1.27E+00
Nitrate	MCL	1.00E+01	6.02E+02	6.02E+01
Nitrite	Noncancer	2.94E+00	5.22E+00	1.78E+00
Selenium	Noncancer	1.47E-01	3.56E-01	2.43E+00
Thallium	Noncancer	2.35E-03	4.52E-02	1.93E+01
Vanadium	Noncancer	2.06E-01	4.78E-01	2.33E+00
Analytes Below Risk Criteria[1]				
Aluminum	Noncancer	2.94E+01	2.30E+01	7.84E-01
Barium	Noncancer	5.89E+00	3.02E-01	5.15E-02
Beryllium	Noncancer	5.87E-02	5.68E-03	9.67E-02
Chromium (III)	Noncancer	4.40E+01	3.66E-01	8.31E-03
Copper	Noncancer	2.93E-01	2.84E-01	9.69E-01
Mercury	Noncancer	8.81E-03	2.50E-04	2.84E-02
Silver	Noncancer	1.47E-01	5.00E-03	3.41E-02
Strontium	Noncancer	1.76E+01	8.74E+00	4.96E-01
Zinc	Noncancer	8.81E+00	6.70E-01	7.60E-02

[1] Risk criteria are 1E-05 cancer risk or a hazard quotient (HQ) of 1E+00 for noncancer endpoints.
HBN = health-based number
90th percentile = 90th percentile SI porewater concentration
HQ = hazard quotient
MCL = maximum contaminant level

Table K-2. CCW Surface Impoundment (SI) Human Health Screening Results: Groundwater-to-Surface-Water (Fish Ingestion) Pathway

Chemical	Benchmark Type	HBN (mg/L)	2002 SI Porewater	
			90th Percentile	HQ (Cancer Risk)
Analytes Exceeding Risk Criteria[1]				
Arsenic	Cancer	0.23	5.18E+00	(2.24E-04)
Arsenic	Noncancer	0.71	5.18E+00	7.28E+00
Cadmium	Noncancer	0.035	1.31E-01	3.73E+00
Mercury	Noncancer	3.85E-06	2.50E-04	6.50E+01
Selenium	Noncancer	0.038	3.56E-01	9.50E+00
Thallium	Noncancer	0.008	4.52E-02	5.69E+00
Analytes Below Risk Criteria[1]				
Antimony	AWQ	4.3	6.40E-02	1.49E-02
Beryllium	Noncancer	1.00	5.68E-03	5.69E-03
Chromium (III)	Noncancer	23,700	3.66E-01	1.54E-05
Chromium (VI)	Noncancer	47	3.66E-01	7.72E-03
Copper[2]	AWQ	1.3	2.84E-01	2.18E-01
Molybdenum	Noncancer	12	1.00E+01	8.43E-02
Nickel	Noncancer	237	7.49E-01	3.16E-03
Zinc	Noncancer	8.13	6.70E-01	8.24E-02

[1] Risk criteria are 1E-05 cancer risk or a hazard quotient (HQ) of 1E+00 for noncancer endpoints.
[2] Fish bioconcentration factor values for copper are zero. HBN based on National Ambient Water Quality Criteria.
HBN = health-based number
90th percentile = 90th percentile SI porewater concentration
HQ = hazard quotient
AWQ = National Ambient Water Quality Criteria
MCL = maximum contaminant level

Table K-3. CCW Landfill Leachate Human Health Screening Results: Groundwater-to-Drinking-Water Pathway

Chemical	Benchmark Type	HBN (mg/L)	2002 Landfill Leachate	
			90th Percentile	HQ(Cancer Risk)
Analytes Exceeding Risk Criteria[1]				
Antimony	Noncancer	1.17E-02	2.61E-01	2.22E+01
Arsenic	Cancer	2.86E-03	3.94E-01	(1.38E-03)
Arsenic	Noncancer	8.81E-03	3.94E-01	4.48E+01
Boron	Noncancer	5.87E+00	1.06E+01	1.80E+00
Cadmium	Noncancer	1.47E-02	4.94E-02	3.37E+00
Chromium (VI)	Noncancer	8.81E-02	2.00E-01	2.27E+00
Cobalt	Noncancer	8.81E-03	8.25E-02	9.33E+00
Fluoride	Noncancer	3.52E+00	6.34E+00	1.80E+00
Lead	MCL	1.50E-02	2.39E-01	1.59E+01
Molybdenum	Noncancer	1.47E-01	6.16E-01	4.20E+00
Nitrite	Noncancer	2.94E+00	3.47E+00	1.18E+00
Selenium	Noncancer	1.47E-01	1.76E-01	1.20E+00
Thallium	Noncancer	2.35E-03	5.00E-02	2.13E+01
Vanadium	Noncancer	2.06E-01	4.50E-01	2.19E+00
Analytes Below Risk Criteria[1]				
Aluminum	Noncancer	2.94E+01	1.05E+01	3.58E-01
Barium	Noncancer	5.89E+00	1.60E+00	2.73E-01
Beryllium	Noncancer	5.87E-02	1.58E-02	2.70E-01
Chromium (III)	Noncancer	4.40E+01	2.00E-01	4.54E-03
Copper	Noncancer	2.93E-01	1.50E-01	5.12E-01
Cyanide	Noncancer	5.87E-01	6.32E-02	1.08E-01
Manganese	Noncancer	1.38E+00	1.37E+00	9.92E-01
Mercury	Noncancer	8.81E-03	2.69E-03	3.06E-01
Nickel	Noncancer	5.87E-01	3.09E-01	5.27E-01
Nitrate	MCL	1.00E+01	2.83E+00	2.83E-01
Silver	Noncancer	1.47E-01	3.95E-02	2.69E-01
Strontium	Noncancer	1.76E+01	9.70E+00	5.51E-01
Zinc	Noncancer	8.81E+00	1.94E+00	2.20E-01

[1] Risk criteria are 1E-05 cancer risk or a hazard quotient (HQ) of 1E+00 for noncancer endpoints, applied to 90th percentile concentrations.

HBN = health-based number
90th percentile = 90th percentile concentration
HQ = hazard quotient
MCL = maximum contaminant level

Table K-4. CCW Landfill Leachate Human Health Screening Results: Groundwater-to-Surface-Water Pathway

Chemical	Benchmark Type	HBN (mg/L)	2002 Landfill Leachate	
			90th Percentile	HQ (Cancer Risk)
Analytes Exceeding Risk Criteria[1]				
Arsenic	Cancer	0.23	3.94E-01	(1.71E-05)
Cadmium	Noncancer	0.035	4.94E-02	1.41E+00
Mercury	Noncancer	3.85E-06	2.69E-03	7.00E+02
Selenium	Noncancer	0.038	1.76E-01	4.69E+00
Thallium	Noncancer	0.008	5.00E-02	6.29E+00
Analytes Below Risk Criteria[1]				
Antimony	AWQ	4.3	2.61E-01	6.07E-02
Arsenic	Noncancer	0.71	3.94E-01	5.54E-01
Beryllium	Noncancer	1.00	1.58E-02	1.59E-02
Chromium (III)	Noncancer	23,700	2.00E-01	8.44E-06
Chromium (VI)	Noncancer	47	2.00E-01	4.22E-03
Copper[2]	AWQ	1.3	1.50E-01	1.15E-01
Cyanide	AWQ	222	6.32E-02	2.85E-04
Molybdenum	Noncancer	12	6.16E-01	5.20E-02
Nickel	Noncancer	237	3.09E-01	1.30E-03
Zinc	Noncancer	8.13	1.94E+00	2.38E-01

[1] Risk criteria are 1E-05 cancer risk or a hazard quotient (HQ) of 1E+00 for noncancer endpoints, applied to 90th percentile concentrations.

[2] Fish bioconcentration factor values for copper are zero. HBN based on National Ambient Water Quality Criteria.

HBN = health-based number90th percentile = 90th percentile concentration

HQ = hazard quotient

AWQ = National Ambient Water Quality Criteria

MCL = maximum contaminant level

Table K-5. Surface Impoundment Ecological Screening Results: Direct Surface Impoundment and Groundwater-to-Surface-Water Pathways

Chemical	CSCL (mg/L)	2002 SI Porewater 90th Percentile (mg/L)	2002 SI Porewater HQ	1998 SI Water 95th Percentile (mg/L)	1998 SI Water HQ
Analytes Exceeding Risk Criterion[1]					
Aluminum	8.70E-02	2.30E+01	2.65E+02	5.11E+00	5.87E+01
Arsenic III	1.50E-01	5.18E+00	3.45E+01	5.50E-01	3.67E+00
Arsenic IV	8.10E-03	5.18E+00	6.39E+02	5.50E-01	6.79E+01
Barium	4.00E-03	3.02E-01	7.54E+01	7.12E-01	1.78E+02
Boron	1.60E-03	7.52E+01	4.70E+04	4.60E+02	2.88E+05
Cadmium	2.50E-03	1.31E-01	5.23E+01	2.50E-01	1.00E+02
Chromium VI	1.10E-02	3.66E-01	3.33E+01	2.67E-02	2.43E+00
Cobalt	2.30E-02	6.27E+00	2.73E+02	1.00E-02	4.35E-01
Copper	9.30E-03	2.84E-01	3.05E+01	3.90E-01	4.19E+01
Lead	3.01E-04	1.77E-01	5.88E+02	2.50E-01	8.31E+02
Mercury	1.90E-07	2.50E-04	1.32E+03	1.50E-03	7.89E+03
Nickel	5.20E-02	7.49E-01	1.44E+01	6.00E-01	1.15E+01
Selenium IV	2.80E-02	3.56E-01	1.27E+01	7.80E+00	2.79E+02
Selenium total	5.00E-03	3.56E-01	7.13E+01	7.80E+00	1.56E+03
Selenium VI	9.50E-03	3.56E-01	3.75E+01	7.80E+00	8.21E+02
Silver	3.60E-04	5.00E-03	1.39E+01	5.00E-03	1.39E+01
Vanadium	2.00E-02	4.78E-01	2.39E+01	8.00E-01	4.00E+01
Analytes Not Exceeding Risk Criterion[1]					
Antimony	3.00E-02	6.40E-02	2.13E+00	1.37E-01	4.57E+00
Beryllium	6.60E-04	5.68E-03	8.61E+00	1.00E-03	1.52E+00
Chromium III	8.60E-02	3.66E-01	4.26E+00	4.00E-01	4.65E+00
Molybdenum	3.70E-01	1.00E+00	2.70E+00	5.00E-01	1.35E+00
Thallium	1.20E-02	4.52E-02	3.77E+00	5.00E-02	4.17E+00
Zinc	1.20E-01	6.70E-01	5.58E+00	6.70E-01	5.58E+00

[1] Risk criterion is a hazard quotient (HQ) of 10 (for direct exposure to impoundment waters).
SI = surface impoundment
CSCL = chemical stressor concentration level

Table K-6. Landfill Ecological Screening Results: Groundwater-to-Surface-Water Pathway

Chemical	CSCL (mg/L)	2002 - Landfill Leachate	
		90th Percentile (mg/L)	HQ
Analytes Exceeding Risk Criterion[1]			
Aluminum	8.70E-02	1.05E+01	1.21E+02
Arsenic IV	8.10E-03	3.94E-01	4.87E+01
Barium	4.00E-03	1.60E+00	4.01E+02
Beryllium	6.60E-04	1.58E-02	2.40E+01
Boron	1.60E-03	1.06E+01	6.61E+03
Cadmium	2.50E-03	4.94E-02	1.98E+01
Chromium VI	1.10E-02	2.00E-01	1.82E+01
Copper	9.30E-03	1.50E-01	1.61E+01
Lead	3.01E-04	2.39E-01	7.94E+02
Mercury	1.90E-07	2.69E-03	1.42E+04
Selenium total	5.00E-03	1.76E-01	3.52E+01
Selenium VI	9.50E-03	1.76E-01	1.85E+01
Silver	3.60E-04	3.95E-02	1.10E+02
Vanadium	2.00E-02	4.50E-01	2.25E+01
Zinc	1.20E-01	1.94E+00	1.61E+01
Analytes Not Exceeding Risk Criterion[1]			
Antimony	3.00E-02	2.61E-01	8.70E+00
Arsenic III	1.50E-01	3.94E-01	2.63E+00
Chromium III	8.60E-02	2.00E-01	2.33E+00
Cobalt	2.30E-02	8.25E-02	3.59E+00
Molybdenum	3.70E-01	6.16E-01	1.67E+00
Nickel	5.20E-02	3.09E-01	5.95E+00
Selenium IV	2.80E-02	1.76E-01	6.28E+00
Thallium	1.20E-02	5.00E-02	4.17E+00

[1] Risk criterion is a hazard quotient (HQ) of 10
CSCL = chemical stressor concentration level

Appendix L. Time to Peak Concentration at Receptor Well for Selected CCW Constituents

L.1 Introduction

This appendix presents plots of arrival times for the peak well concentrations used to calculate groundwater-to-drinking-water risks for selected CCW constituents (arsenic III and V, boron, cobalt, selenium IV and VI, and thallium[1]). The arrival times are plotted as cumulative distributions for surface impoundments and landfills**.** These constituents were selected to represent the chemicals with the highest estimated risks and to span the range of mobility in the subsurface.

Groundwater pathway modeling conducted in support of the CCW risk assessment consisted of probabilistic fate and transport simulations of mostly metal constituents present in three different waste types (ash, ash and coal, and fluidized bed combustion wastes) managed in landfills and surface impoundments. Three liner designs were also considered: no liner; a 3-foot clay liner; and a composite liner (a composite of geomembrane, geosynthetic clays, and/or compacted clays), assigned to each CCW waste management unit (WMU) based on liner type data in the EPRI database (see **Appendix B**). The predicted groundwater concentrations were used to estimate potential risks to humans and the environment exposed to the modeled CCW constituents.

Among the inputs to the model were distributions of infiltration rates of water through the landfills and surface impoundments corresponding to each of the three liner types. Among the outputs generated by the groundwater pathway fate and transport model were the peak concentration observed at the receptor well and the time at which the peak was observed. For each probabilistic simulation scenario (a constituent in a particular waste type managed in a particular type of WMU), approximately 10,000 sets of model inputs generated an equivalent number of groundwater observations. Some were non-zero concentrations, others were zero. For these zero-value observations, the model also assigned a value of zero to arrival time. Zero-value observations can be attributed to zero-value infiltration rates (which occur only for WMUs with composite liners); in that case, no mass leaves the WMU and there is no time of travel. Zero-value observations can also be attributed to fate and transport conditions that retard the movement of a constituent from the WMU through the subsurface to the extent that the dissolved component was not observed within the established maximum allowable timeframe (10,000 years). In this case, the time of travel is greater than 10,000 years.

To better understand the time frames in which risks associated with exposures to contaminated groundwater may occur, an analysis was performed to graphically represent distributions of arrival time of the peak groundwater concentrations at the nearby drinking water well. The analysis was performed across all waste types with respect to liner and WMU type.

[1] Thallium was not modeled in the surface impoundment scenario, and thus no arrival times were calculated here.

What follows is a description of how the peak concentrations and their arrival times were treated to create the plots presented in this appendix, including the treatment of zero-value observations.

L.2 Methodology

Given a constituent managed in a particular type of WMU (e.g., arsenic in landfills), all infiltration rates and their corresponding peak concentrations and arrival times predicted by the model were extracted from the input/output data for simulations across all waste types in which the selected constituent was found. The triplets of data needed to prepare the graphs—infiltration rate, peak concentration, and arrival time—were then filtered from the data and segregated by liner type. Zero-value observed concentrations were treated in the following manner:

- Zero-value observations corresponding to zero-value infiltration rates were assigned an arbitrary value of -1, effectively excluding those data from the graphs. This was appropriate, because when infiltration is zero, there is no plume and no contaminants enter or are transported in groundwater. Only the composite liner scenarios produced zero-value infiltration rates.

- Zero-value observations corresponding to non-zero infiltration rates were assigned an arbitrary arrival time greater than (>) 10,000 years, the maximum simulation timeframe. These data points are also not shown in the plots, as only times up to 10,000 years were visible.

Table L-1 shows the distribution of zero-value concentration observations by WMU and composite liner scenario. The total observations in this table include data points with a modeled arrival time of >10,000 years and those with zero infiltration rates. Note that for surface impoundments, there are fewer model runs (observations) for thallium because thallium results are not available for ash and coal waste streams because of very limited data in the CCW constituent database.

Table L-1. Distribution of Zero-Value Concentrations

WMU Type	Total Observations[a] (Number)	Zero Infiltration Rates (Number)	Zero Infiltration Rates[b] (%)	Composite Liner Observations (Number)	Composite Liner Zero Infiltration Rates (%)
Landfill	29,717	3,538	11.9%	4,847	73.0%
Surface Impoundment (As, B, Se)[c]	19,825	500	2.5%	1,406	35.6%
Surface Impoundment (Tl)[d]	9,905	389	3.9%	1,130	34.4%

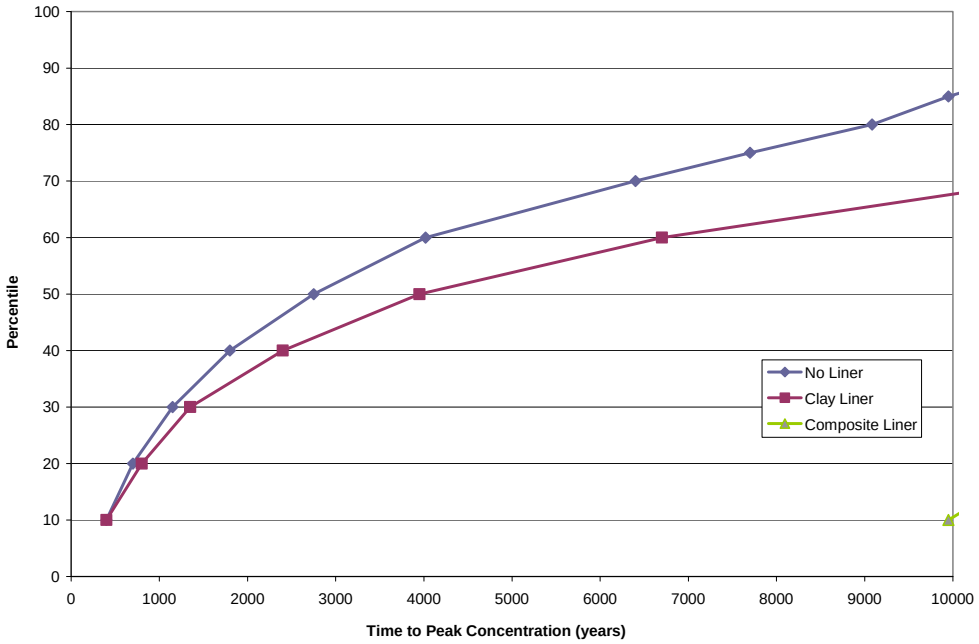
[a] Per constituent across all waste types and liners.
[b] Out of all observations.
[c] Observations for arsenic, boron, cobalt, and selenium; all were modeled in both ash and ash and coal waste streams managed in surface impoundments.
[d] Observations for thallium only, which was detected only in ash waste streams managed in surface impoundments.

After zero infiltration rate observations were filtered from each data set, percentiles of arrival time of the peak observed concentration were plotted on the y-axis by liner type and WMU (**Figures L-1** through **L-21**). The x-axis range for landfills is 0 to 10,000 years. For

surface impoundments, plots are provided on both the full 0 to 10,000-year time frame and a shorter time frame, so that the shape of the cumulative distribution can be seen for the lower time-of-travel range characteristic of these facilities.

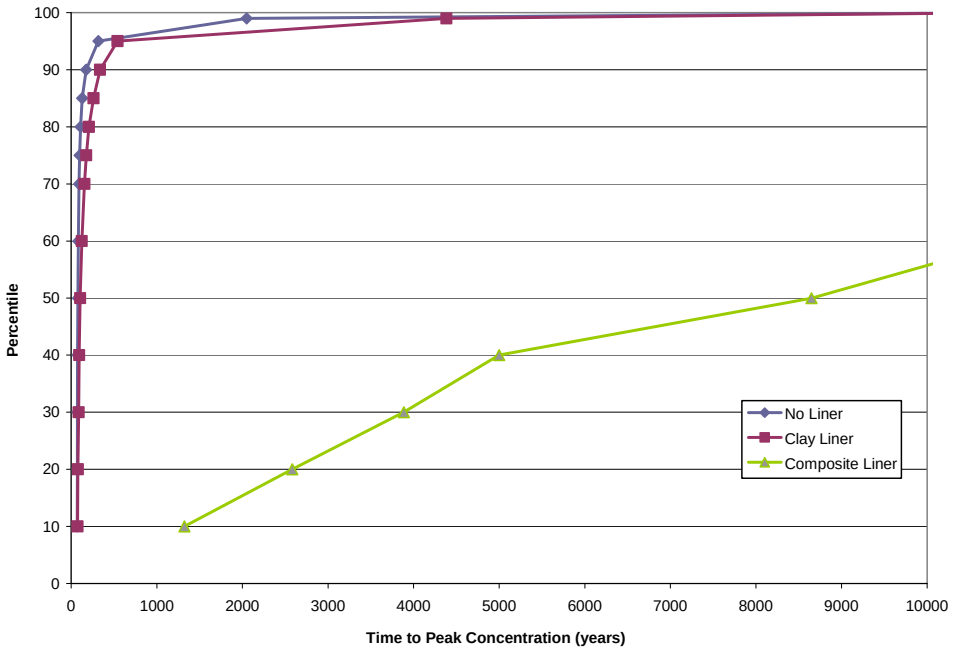
The figures are organized alphabetically by metal, and there are three figures for each metal: landfills, surface impoundments (0–10,000 years), and surface impoundments (shorter time frame).

The shorter arrival times for clay-lined landfills compared to unlined landfills are an artifact of the fact that liners were modeled at each landfill as reported in the EPRI survey, and each landfill location has a different subsurface geology. The shorter arrival times mainly reflect more transmissive soils and aquifer materials at the clay-lined facility locations.



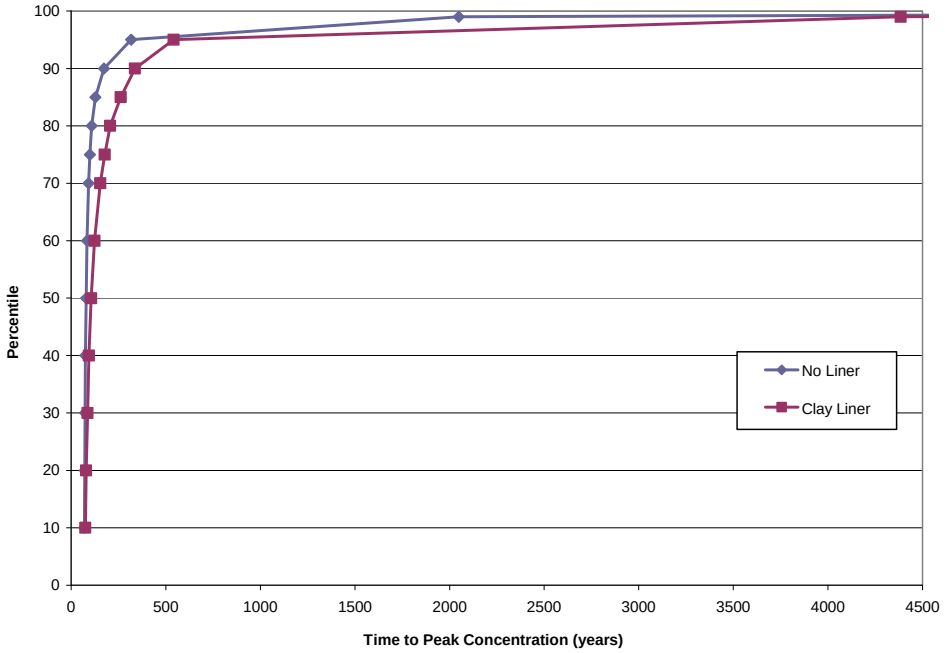
73% of composite liner results have no infiltration and are not plotted on this graph.

Figure L-1. Time to peak distribution for arsenic III: landfills, all waste types.



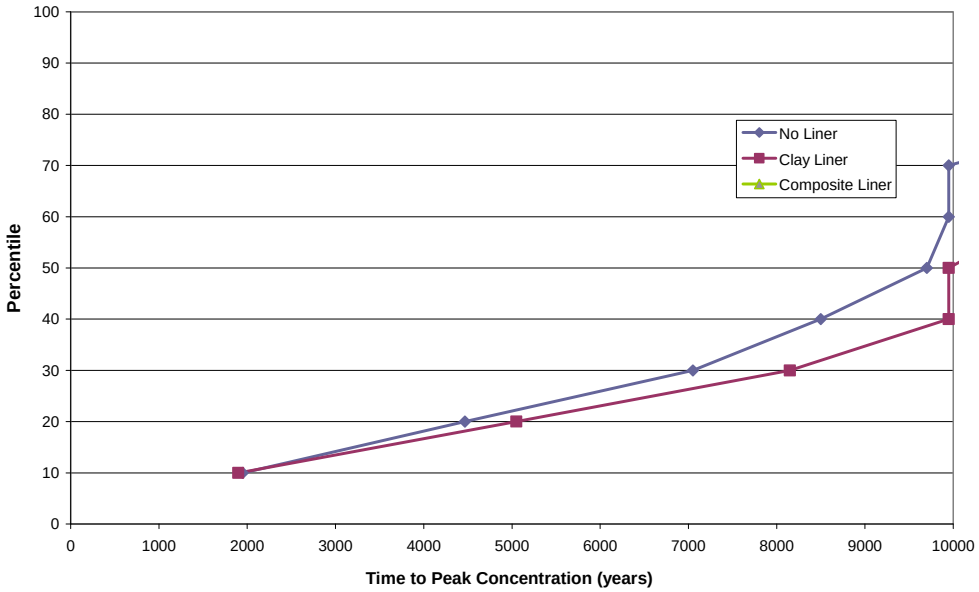
35.6% of composite liner results have no infiltration and are not plotted on this graph.

Figure L-2. Time to peak distribution for arsenic III: surface impoundments, all waste types, full 10,000 year time frame.



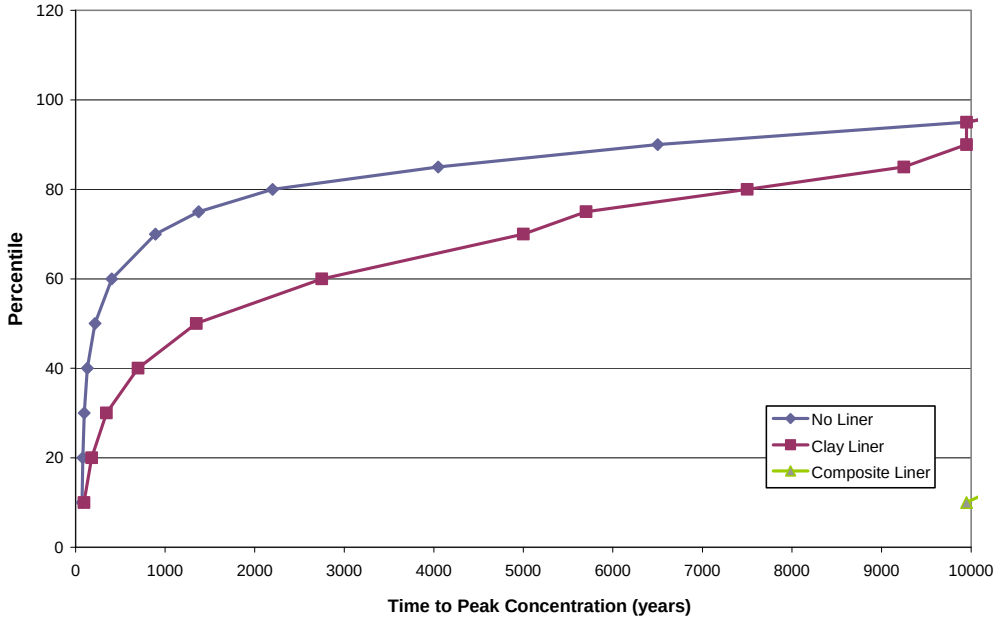
35.6% of composite liner results have no infiltration and are not plotted on this graph.

Figure L-3. Time to peak distribution for arsenic III: surface impoundments, all waste types, shorter time frame.



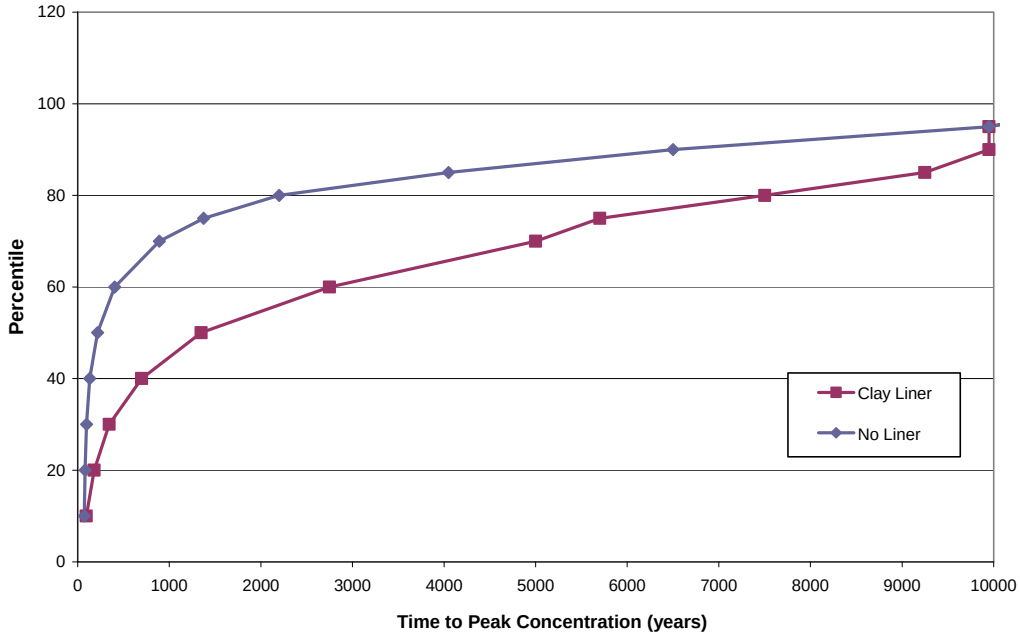
73% of composite liner results have no infiltration and are not plotted on this graph.

Figure L-4. Time to peak distribution for arsenic V: landfills, all waste types.



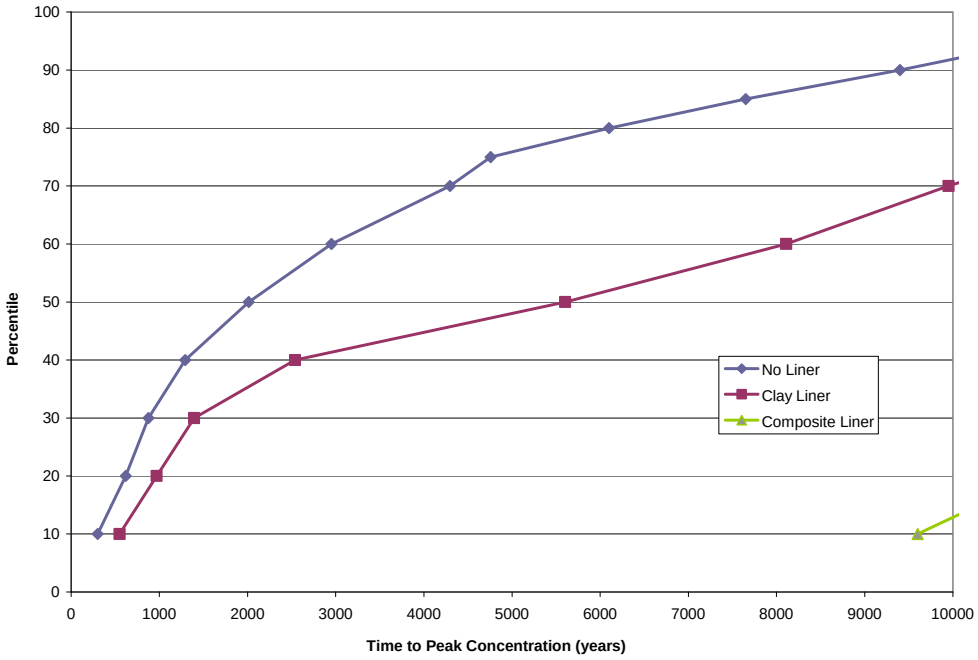
35.6% of composite liner results have no infiltration and are not plotted on this graph.

Figure L-5. Time to peak distribution for arsenic V: surface impoundments, all waste types, full 10,000 year time frame.



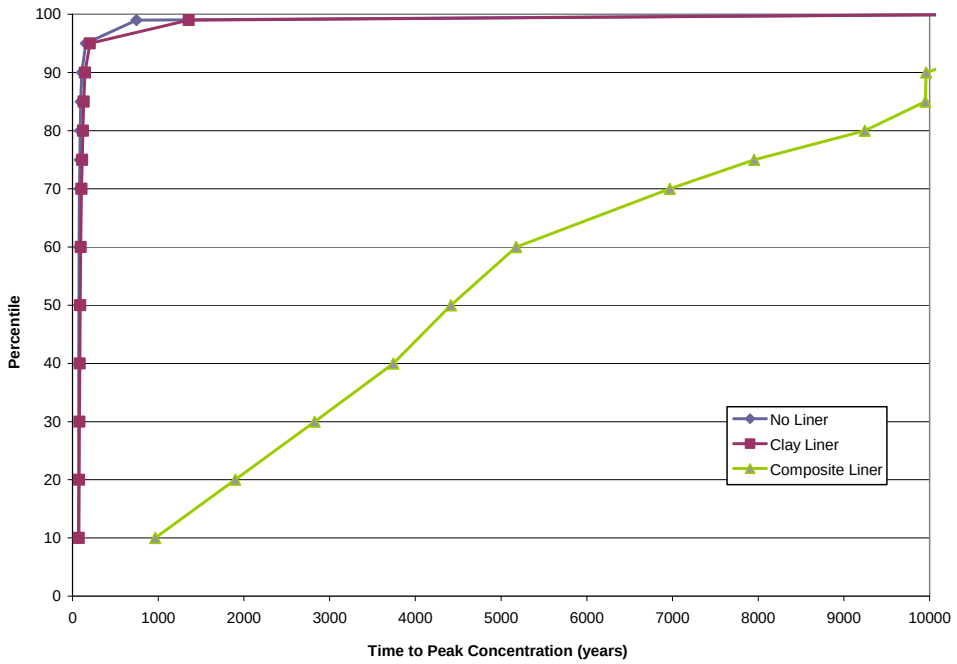
35.6% of composite liner results have no infiltration and are not plotted on this graph.

Figure L-6. Time to peak distribution for arsenic V: surface impoundments, all waste types, shorter time frame.



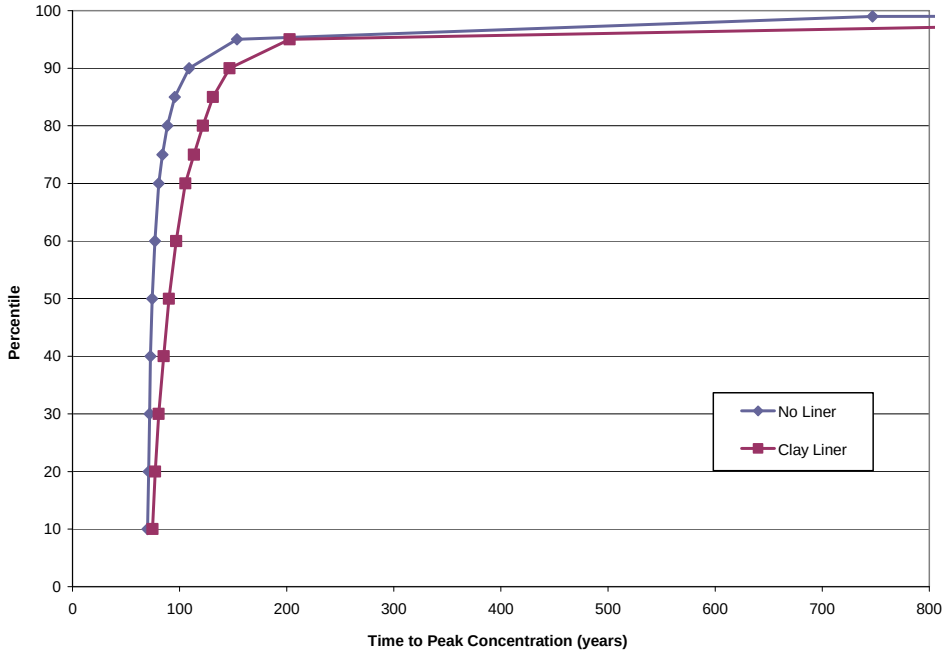
73% of composite liner results have no infiltration and are not plotted on this graph.

Figure L-7. Time to peak distribution for boron: landfills, all waste types.



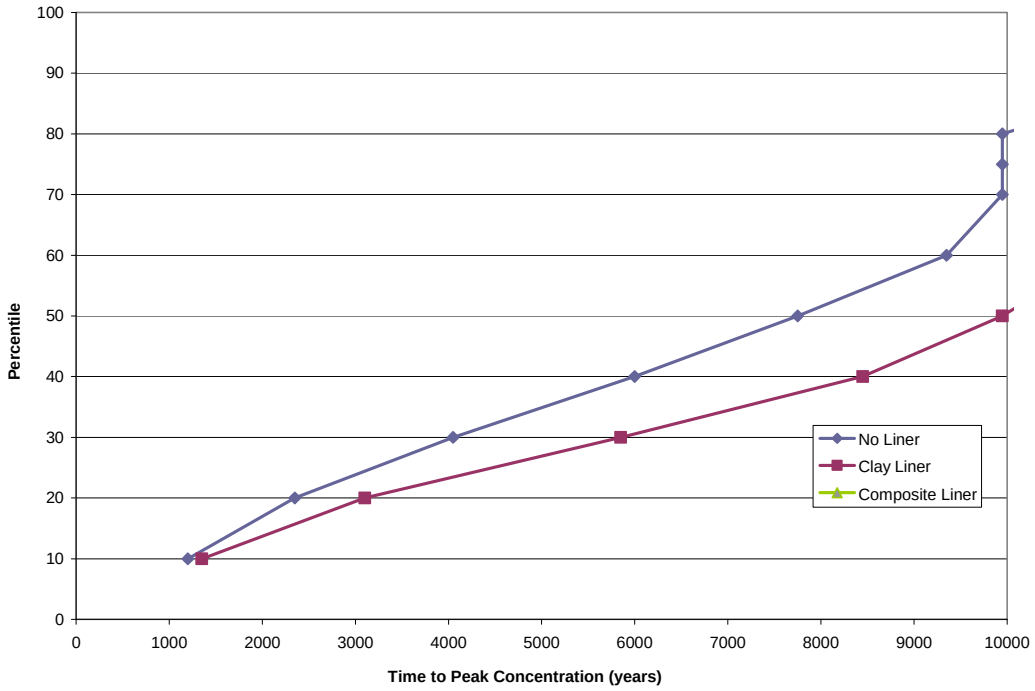
35.6% of composite liner results have no infiltration and are not plotted on this graph.

Figure L-8. Time to peak distribution for boron: surface impoundments, all waste types, full 10,000 year time frame.



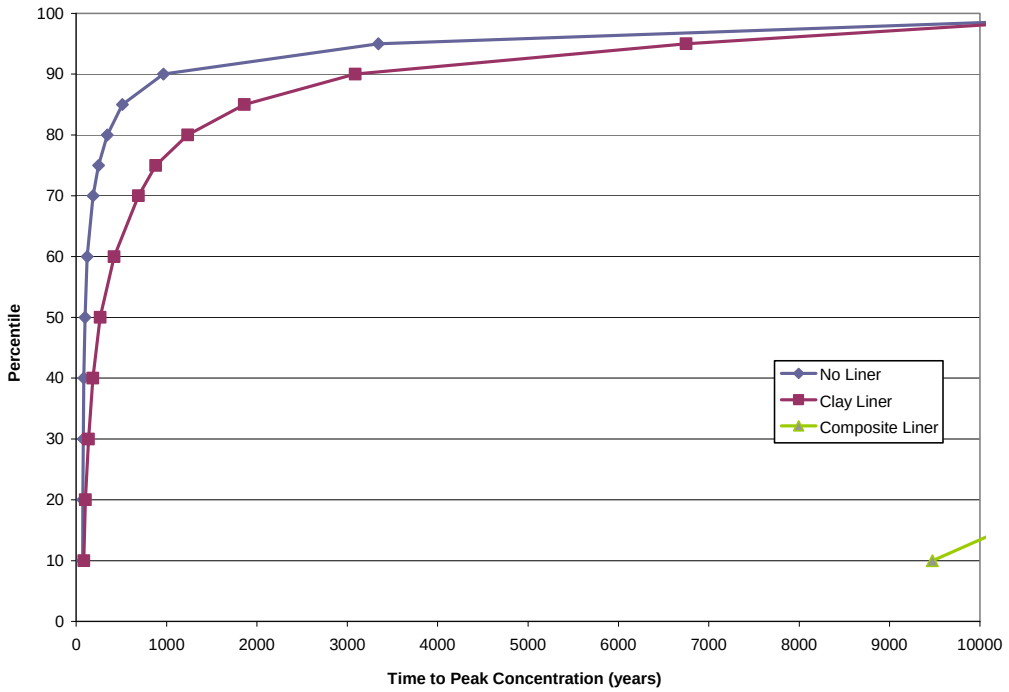
35.6% of composite liner results have no infiltration and are not plotted on this graph.

Figure L-9. Time to peak distribution for boron: surface impoundments, all waste types, shorter time frame.



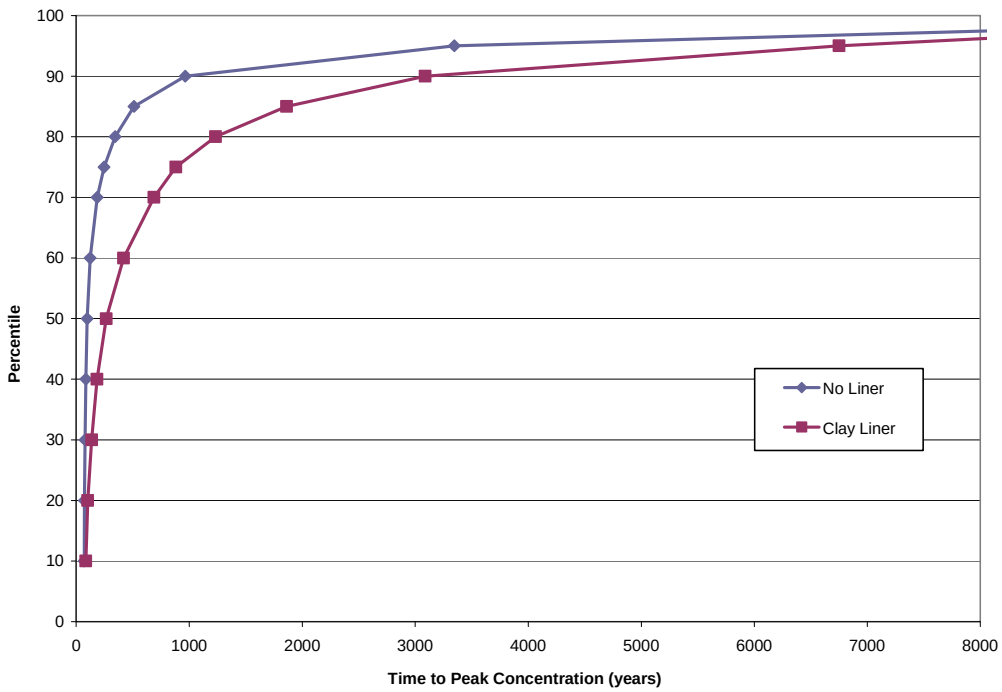
73% of composite liner results have no infiltration and are not plotted on this graph.

Figure L-10. Time to peak distribution for cobalt: landfills, all waste types.



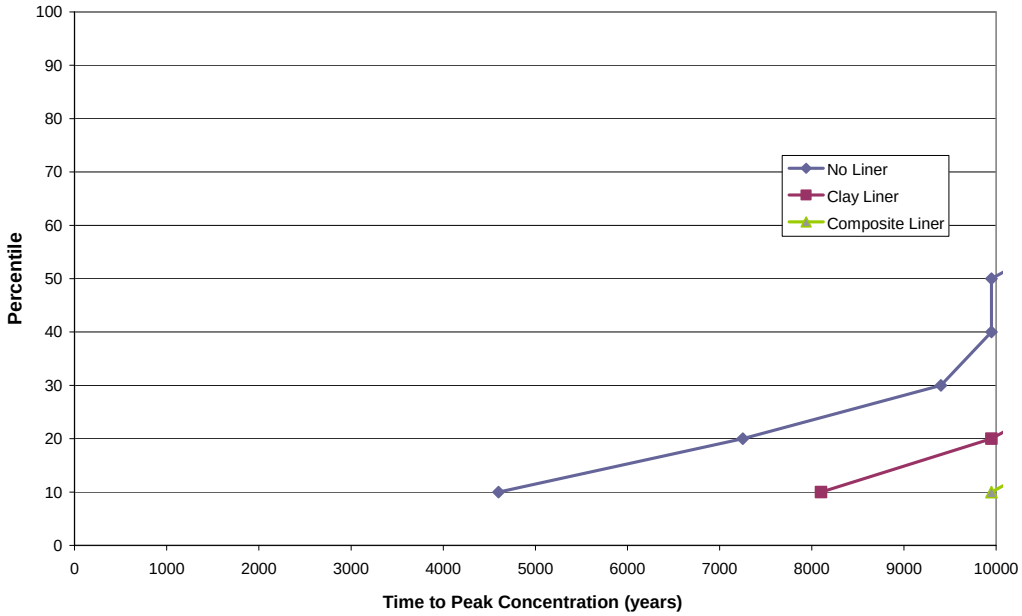
35.6% of composite liner results have no infiltration and are not plotted on this graph.

Figure L-11. Time to peak distribution for cobalt: surface impoundments, all waste types, full 10,000 year time frame.



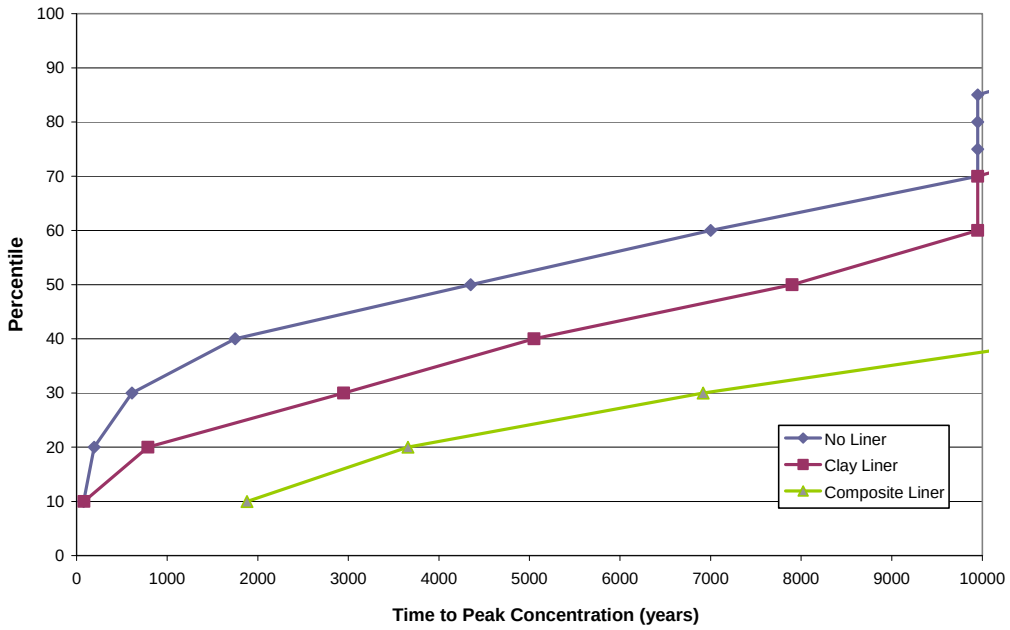
35.6% of composite liner results have no infiltration and are not plotted on this graph.

Figure L-12. Time to peak distribution for cobalt: surface impoundments, all waste types, shorter time frame.



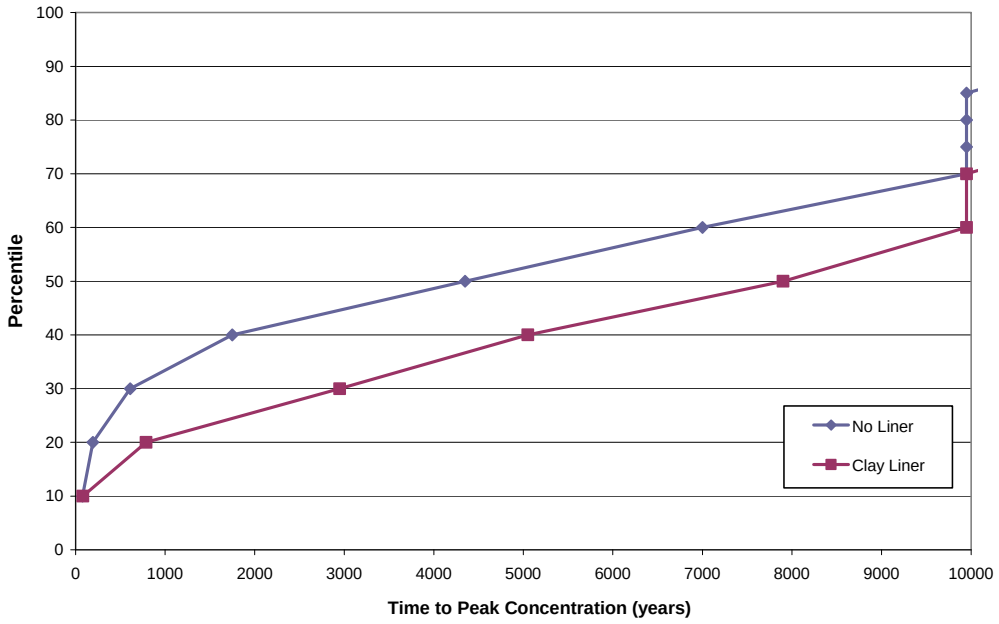
73% of composite liner results have no infiltration and are not plotted on this graph.

Figure L-13. Time to peak distribution for selenium IV: landfills, all waste types.



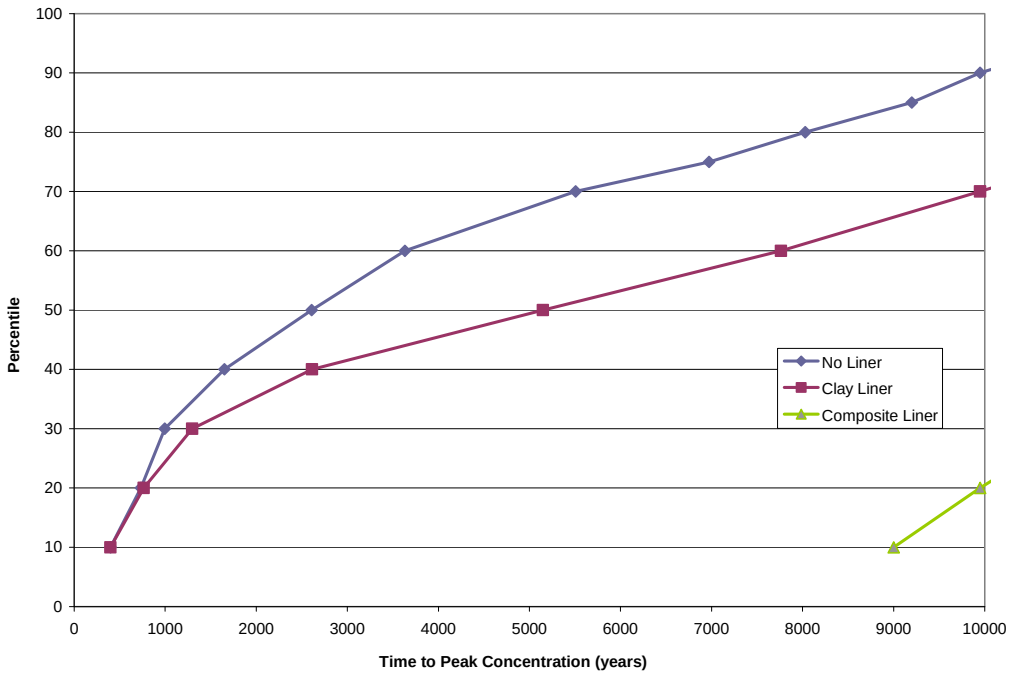
35.6% of composite liner results have no infiltration and are not plotted on this graph.

Figure L-14. Time to peak distribution for selenium IV: surface impoundments, all waste types, full 10,000 year time frame.



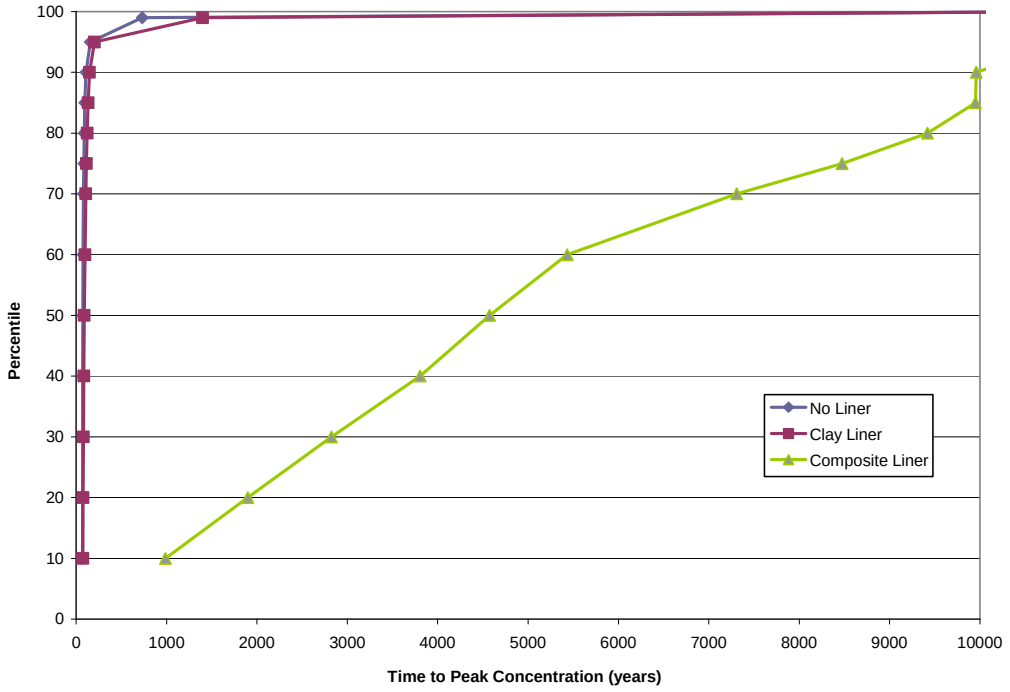
35.6% of composite liner results have no infiltration and are not plotted on this graph.

Figure L-15. Time to peak distribution for selenium IV: surface impoundments, all waste types, shorter time frame.



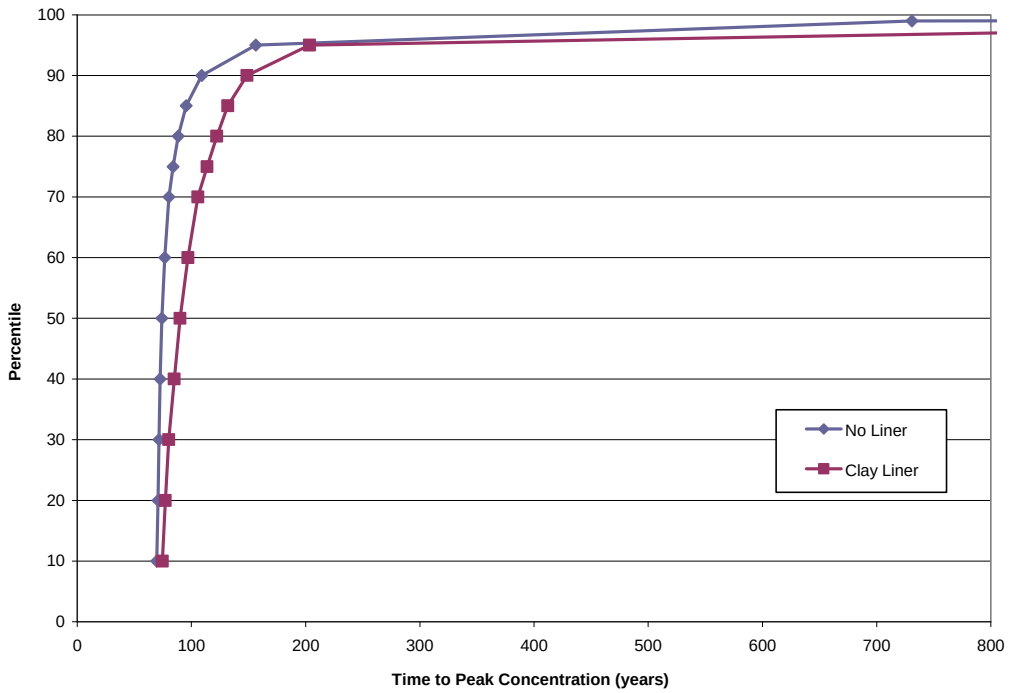
73% of composite liner results have no infiltration and are not plotted on this graph.

Figure L-16. Time to peak distribution for selenium VI: landfills, all waste types.



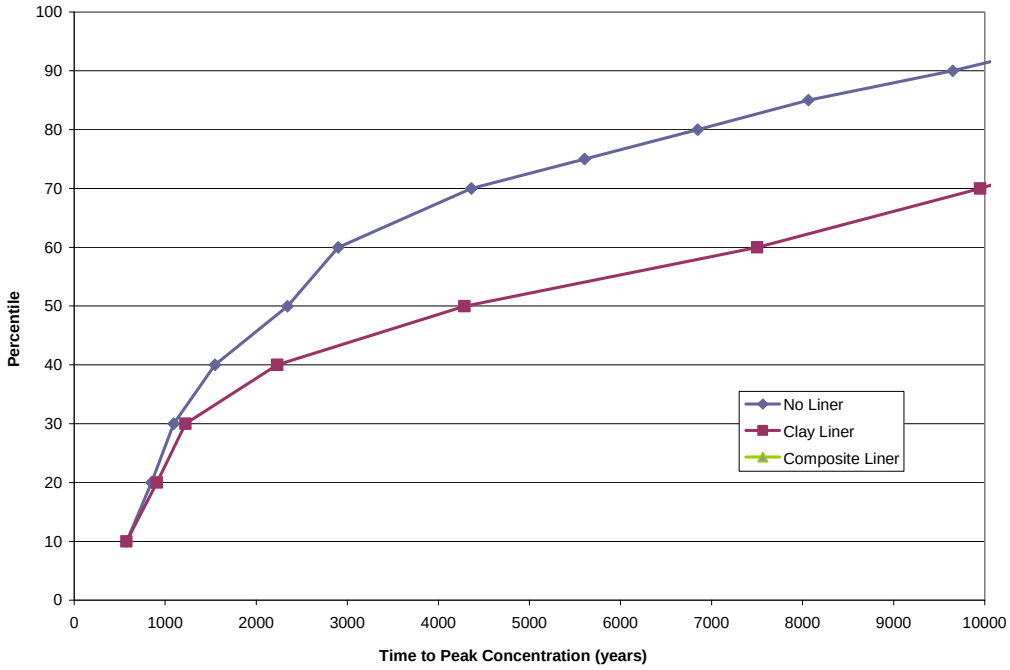
35.6% of composite liner results have no infiltration and are not plotted on this graph.

Figure L-17. Time to peak distribution for selenium VI: surface impoundments, all waste types, full 10,000 year time frame.



35.6% of composite liner results have no infiltration and are not plotted on this graph.

Figure L-18. Time to peak distribution for selenium VI: surface impoundments, all waste types, shorter time frame.



73% of composite liner results have no infiltration and are not plotted on this graph.

Figure L-19. Time to peak distribution for thallium: landfills, all waste types.