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Assessment of Industrial Sounds and Vibrations Received in Artificial Polar Bear Dens, Flaxman Island, Alaska

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ABSTRACT

Noise and ground vibration data were collected at man-made dens in polar bear (*Ursus maritimus*) habitat on Flaxman Island, Alaska, in the vicinity of remediation activities involving the use of heavy equipment and blasting. The study was conducted to determine the absolute sound levels of various industrial activities received in artificial polar bear dens and to estimate potential exposure of denning polar bears to noise and vibration. Comparison of sound levels, measured with microphones placed outside and inside the dens, permitted estimation of the sound-insulating properties of the dens. Vibration data were acquired from sensors placed in the tundra and snow of the den floors. Measurements of noise and vibration were made for the following vehicles: front-end loader, trimmer, gravel hauler, fuel truck, pickup truck, Hägglunds tracked vehicle, and a Tucker Sno-Cat. A single blast event, which was used to cut a well pipe, was recorded in the dens. In addition, noise and ground vibration data were obtained for Bell 212 and Bell 206 helicopters during maneuvers around the dens. The maximum distance vehicle noise was detected above background noise in the dens ranged from < 500 m to 2000 m. In-den sound pressure levels (SPL) for vehicles at the closest point of approach ranged from 37 – 55 dB re 20 μPa. Of the personnel transport vehicles regularly used on the north slope the Hägglunds tracked vehicle produced the loudest noises near the den, while the Tucker Sno-Cat and pick-up trucks produced the quietest. Helicopter noise was well above background levels in the den until helicopters were at least 1000 m from the den. The maximum noise level measured was 82 dB (flat – slow weighting) for the Bell 206 as it hovered 16 m directly above the den. Noise signatures suggest that the Bell 212 and the Bell 206 produce similar broadband noise levels, however, noise from the 212 was concentrated at lower frequencies, suggesting that the Bell 206 may be more audible to polar bears if their hearing is more sensitive to frequencies above 50 Hz than below. The man-made dens were found to be very good at reducing noise exposure. The snow surrounding the man-made dens reduced the level of outside sounds by 25 dB at 50 Hz, and by 40 dB at 1000 Hz. The in-den ambient noise levels for the man-made dens were typically very low. Third-octave band levels for ambient noise levels were less than 40 dB below 100 Hz, and less than 20 dB for bands greater than 100 Hz. Low frequency sound levels were directly related to wind speed.

1 INTRODUCTION

This technical report provides absolute measurements of sound and vibration levels produced by remediation activities carried out by the oil and gas industry during winter on the North Slope of Alaska. Measurements of sound and vibration levels were made inside and outside of man-made polar bear (*Ursus maritimus*) dens while industrial activities were being performed on Flaxman Island in early March 2002. Monitored activities included heavy equipment performing excavations of two drilling reserve pits, an in-well blast, and several types of vehicles traveling along a road on Flaxman Island. These operations were being carried out as part of a project to remove drilling muds and cuttings from two reserve pits on the island. In addition, we manipulated the operations of two types of helicopters and tracked all-terrain vehicles in order to better characterize sounds and vibrations produced during various activities.

In recent years as petroleum exploration and development activities in the arctic have expanded, there has been an increasing concern that oil and gas activities could potentially disturb polar bears and their habitat (Geraci and St. Aubin 1980; Lentfer 1990), including a concern that noise and vibration may propagate into dens and disturb denning polar bears. Sound and vibration produced by industrial activities during the winter may impact polar bears due to their year-round residency on the North Slope. From December to April, industry activities coincide with the period when female polar bears give birth and care for their young in maternal dens (Amstrup and Gardner 1994). There is concern that noise and vibration caused by industrial activities may disturb denning bears during this sensitive period.

In the Beaufort Sea, female polar bears usually enter maternity dens from late October through early December. Females and cubs generally emerge from their dens in mid March or early April (Amstrup 2000). These dens are excavated in accumulations of snow on land or offshore pack ice (Amstrup 2000). Amstrup and Gardner (1994) reported that 53% of polar bear natal dens in the Beaufort Sea region occurred on offshore pack ice and 47% occurred on land. Polar bears in Alaska that den on nearshore landfast ice and on land are more likely to encounter industrial activities than bears denning on the offshore pack ice. For example, in 1991, two maternity dens were located within 2.8 km (1.7 mi) of a production facility (Amstrup 1993), and, recently, female polar bear dens have been found near industrial activities on Flaxman Island (G. York, USGS, pers. comm.).

Potential sources of noise and vibration during the ice-covered season include exploratory drilling, vibroseis, production facilities, ice road and ice pad construction, and vehicle and aircraft traffic. Although Blix and Lentfer (1992) documented received sound levels from some petroleum-related activities at man-made dens, there is currently a lack of pertinent information that is necessary to determine whether, industrial noise and vibration effects on polar bears should be mitigated. Industry-produced noise and vibration could have the following effects on denning polar bears:

- loss of denning habitat if pregnant females avoid denning in the vicinity of the noise and vibration sources, and
- decreased cub survival if females with cubs prematurely abandon their dens due to noise disturbance.

To assess disturbance to the wintering polar bear population on the North Slope by the oil and gas industry, denning female polar bears near oilfield activities are located and monitored by the U. S. Geological Survey, Biological Resources Division (USGS) and managed by the U.S. Fish and Wildlife Service (USFWS). The oil and gas industry communicates with the USFWS to determine the location of known dens relative to their activities and supports Forward Looking Infrared (FLIR) surveys to augment this information. In an effort to minimize disturbances to denning polar bears, the petroleum industry is required to avoid all known polar bear dens by 1 mi (1.6 km), unless given special permission by the USFWS after obtaining a Letter of Authorization (LoA) allowing incidental taking (S. Schliebe, USFWS, pers. comm.).

1.1 Noise Effects and Polar Bear Hearing

The ability of an animal to hear a sound is dependent on the following (Richardson et al. 1995): (1) absolute hearing threshold (the lowest sound level that can be detected in the absence of ambient noise), (2) critical ratio (the signal-to-noise ratio required to detect a tonal sound in the presence of background noise), (3) the ability to localize sound direction at the frequencies under consideration, and (4) the ability to discriminate among sounds of different frequencies and intensities. Audiograms to characterize polar bear hearing abilities have not been determined.

The most closely related species to polar bears for which extensive hearing and auditory studies have been conducted is the domestic dog (*Canis canis*), which shares a distant, common ancestry with bears (T. Smith, USGS, pers. comm.). The frequency range for hearing in dogs is approximately 67 Hz to 45 kHz with peak sensitivity between 100-30,000 Hz (Fay 1988). It is not known whether bears perceive and respond to frequencies within this range. However, behavioral responses of polar bears to anthropogenic noise disturbances have been reported for a variety of circumstances (Linnell et al. 2000; Moulton and Williams 2000; Amstrup and Gardner 1994; Amstrup 1993; Stirling and Andriashek 1992).

The effects of noise on marine mammals, including polar bears, are highly variable (Richardson et al. 1995). They could range from: (1) no effect; the noise may be too weak to be heard by the animal; (2) the noise may be audible but not strong enough to elicit a behavioral response; (3) the noise is audible but may or may not elicit a behavioral response; (4) the animal may become habituated or sensitized to the noise if repeated; (5) the noise could be strong enough to mask other important sounds to the marine mammal; and (6) the noise may be loud enough to cause temporary or permanent reduction in hearing sensitivity. The ways in which noise affects marine mammals depends partly on the propagating characteristics of the noise, the propagation medium, environmental factors, ambient noise levels, and the behavior of the animal at the time the noise is received. Noise and vibrations, both natural and anthropogenic, propagate differently through ice, water, land, and air.

Natural ambient noise is the background sound of physical and biological origin, excluding sounds from specific identifiable and localized sources. Industrial noises are only distinguishable from natural sounds if they exceed the detection threshold at corresponding frequencies. Marine mammals are adapted to natural ambient noise in their environment. Therefore, ambient levels are important for understanding the natural environmental variation that influences an animal's ability to detect natural and anthropogenic sounds. For example, in the arctic environment, wind has the greatest influence on the overall ambient noise levels, due to its effect on the ice and water. Ambient noise levels in the air over the Beaufort Sea are expected to be dominated by the sound of breaking ice during the ice-covered and broken ice seasons and by the sound of breaking waves during the open water season (Greene and Buck 1964; Milne and Ganton 1964). Blackwell et al. (2003) reported that the broadband "background" in-air noise in the Beaufort Sea during the winter was 44 dB re 20 μPa.

Airborne industrial noises from oil and gas development activities have been measured on the North Slope. Airborne sounds of drilling and production machinery were recorded during the winter of 2002 near Northstar Island (Blackwell et al. 2003). The maximum broadband (10-10,000 Hz) unweighted sound pressure level (SPL), recorded approximately 220 m from the active Northstar drill rig during oil and gas production, was 80 dB re 20 μPa. Some in-air industrial sounds were detectable by the instruments as far as 9 km (5.6 mi) away (Blackwell et al. 2003). In addition, Blix and Lentfer (1992) measured noise and vibration levels of seismic and petroleum-related activities received in artificial polar bear dens and found that snow suppressed most noise and vibrations. Blix and Lentfer (1992) also noted that industry noise from sources greater than 100 m from the den was not detectable above average background levels inside the den.

1.2 Study Rationale

Prior to the initiation of remediation activities on Flaxman Island (winter 2001-2002) one known polar bear den and three suspected dens, were located along the shoreline of Flaxman Island using Forward Looking Infrared (FLIR) imagery (G. York pers. comm.). The heavy equipment and vehicle traffic along the ice road, heavy equipment operation on the island, explosions, and other activities associated with removal of the reserve pits on Flaxman Island had the potential to disturb the known bear in its den. Given the proximity of these known and suspected dens to industrial activities, this study using man-made dens was initiated to determine the potential level of noise and vibrations received at the known and suspected dens. These data will be used to determine the transmission loss of industrial sounds and vibrations through snow, tundra, and nearshore grounded sea ice, which are all important den habitats for polar bears (Amstrup and Gardner 1994; Amstrup 2000). In addition, through the use of transmission loss modeling we can estimate the received levels of sounds and vibrations at various distances from the source.

This report contains a description of the sounds and vibrations from industrial activities received in man-made polar bear dens. These data will supplement industrial noise and vibration data collected by Blix and Lentfer (1992), Greene (1997), Greene et al. (2000), and Blackwell and Greene (2002). The data from this study will also assist regulatory agencies in evaluating the current monitoring and mitigation measures regarding the proximity of industrial activities to polar bear dens.

1.3 Objectives

The objectives of this project were to:

- document the levels and characteristics of sounds and vibrations produced by remediation activities as they were received in man-made polar bear dens at varying distances from the source, and
- document the levels and characteristics of sounds produced by helicopter overflights as they were received in the man-made polar bear dens.

2 STUDY AREA

The study area was located on Flaxman Island in the central Beaufort Sea (70° 11'N, 146°00'W). Flaxman Island is located east of Prudhoe Bay and was accessible via a 60-mile ice road originating at the Endicott Causeway (Figure 1). A temporary camp was established on the western end of Flaxman Island, which served as the coordinating center for the project and housing for the remediation crew. A 1.5 km (1 mi) ice road on Flaxman Island between Well Sites Alaska State A-1 (hereafter A-1) and Alaska State G-2 (hereafter G-2) was constructed to access the reserve pits.

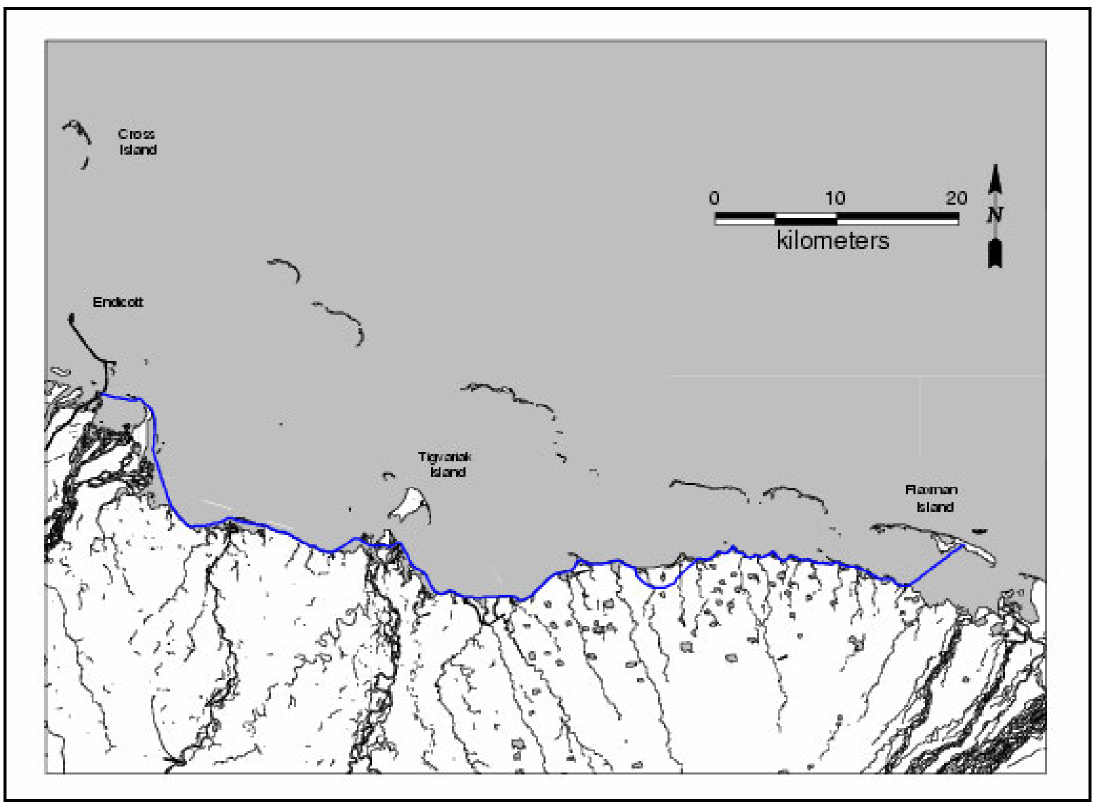

Figure 1: The ice road between the Endicott Causeway and Flaxman Island, Arctic Coastal Plain, Alaska.

2.1 Industrial Activities on Flaxman Island

In July 2000, ExxonMobil Production Company initiated a plan to remove two inactive reserve (A-1 and G-2) and flare pits at exploratory drill sites on Flaxman Island (CH2M HILL 2000). A well near reserve pit A-1 was drilled in 1973, plugged and abandoned in 1974, and another well near G-2 was drilled and plugged in 1983. Bluff erosion along the north shore of Flaxman Island threatened to expose buried wastes from the reserve pits to the Beaufort Sea. The original closure plan called for the excavation of well-bore related drilling wastes along with associated ice and soils, and grinding and injection of these wastes into a Class II injection well drilled at A-1 during the winter 2000-2001. This approach proved to be ineffective and was abandoned in early April 2001. The modified closure plan called for wastes, associated ice, and soils to be transported in gravel haulers along an ice road from Flaxman Island to the Endicott Causeway then along existing gravel roads to Drill Site 4 in the Prudhoe Bay Unit for grinding, injection, and disposal (CH2M HILL 2002). Construction of the ice road from the Endicott Causeway to Flaxman Island, primarily along the nearshore grounded ice, was initiated in December 2001. Remediation activities began on Flaxman Island in the first week of February 2002 and continued through the first week of April 2002. Gravel hauling occurred for approximately 30 days from 1–30 March.

3 METHODS

From 5 to 8 March 2002, we measured characteristics of noise and ground vibrations received outside and inside man-made polar bear dens on Flaxman Island, Alaska. In air sound and ground vibrations resulted from industrial activities on the island that included ice road construction, vehicle traffic on the ice road (on and off the island), excavation activities, and blasting activity. Additionally, we collected acoustic data during experimental trials involving tracked vehicles and helicopters.

3.1 Man-made Polar Bear Dens

3.1.1 Den Construction

During the last week of February 2002, U.S. Geological Survey (USGS) and U.S. Fish and Wildlife Service (USFWS) polar bear biologists excavated eight dens on Flaxman Island, in natural polar bear denning habitat (Durner et al. 2001). Dens were constructed in natural snowdrifts along the north side of the island, approximately 50-100 m from the ice road using hand tools (e.g., snow saw, shovel). After dens were excavated, water was sprayed on the inside walls and ceiling to simulate icing conditions in natural dens caused by animal respiration. Due to logistical constraints, we abandoned four of the dens and concentrated monitoring efforts on the four dens located along the tundra ice road between reserve pits A-1 and G-2 (Table 1, Figure 2). The dens were, as far as practicable, constructed to resemble natural polar bear dens in terms of habitat, physical dimensions, and snow thickness over the dens (Clark et al. 1997; Durner et al. 2003). We assumed that our constructed dens would receive noise and vibrations from industrial activities in the same manner as natural polar bear dens in similar habitat.

3.1.2 Den Instrumentation

From 1 to 3 March 2002, we instrumented the 4 dens with microphones and ground vibration sensors (i.e., accelerometers). Sensors were located in the center of the den (Figure 3). After instrumentation of the den was complete, we filled the den entrance with snow. All temperature-sensitive electronics and recording equipment associated with the sensors were housed outside of the dens in ice-fishing tents (approximately 6 ft x 4 ft x 5 ft). Tents were located approximately 5 m from the den entrance (Figure 4) and were sheltered from the wind by walls constructed of snow blocks.

Table 1: Location and physical description of man-made polar bear dens on Flaxman Island, Alaska, March 2002.

Site	GPS Location (Datum: WGS 84)	Chamber Dimensions (L × W × H)	Snow Depth (ceiling thickness)
Den 5	70°11.2849'N, 146°00.2494'W	52" × 38" × 28"	18"
Den 6	70°11.1894'N, 145°59.7097'W	37" × 47" × 27"	30"
Den 7	70°11.1404'N, 145°59.0879'W	38" × 48" × 28"	22"
Den 8	70°11.0586'N, 145°58.5615'W	40" × 51" × 28"	19"

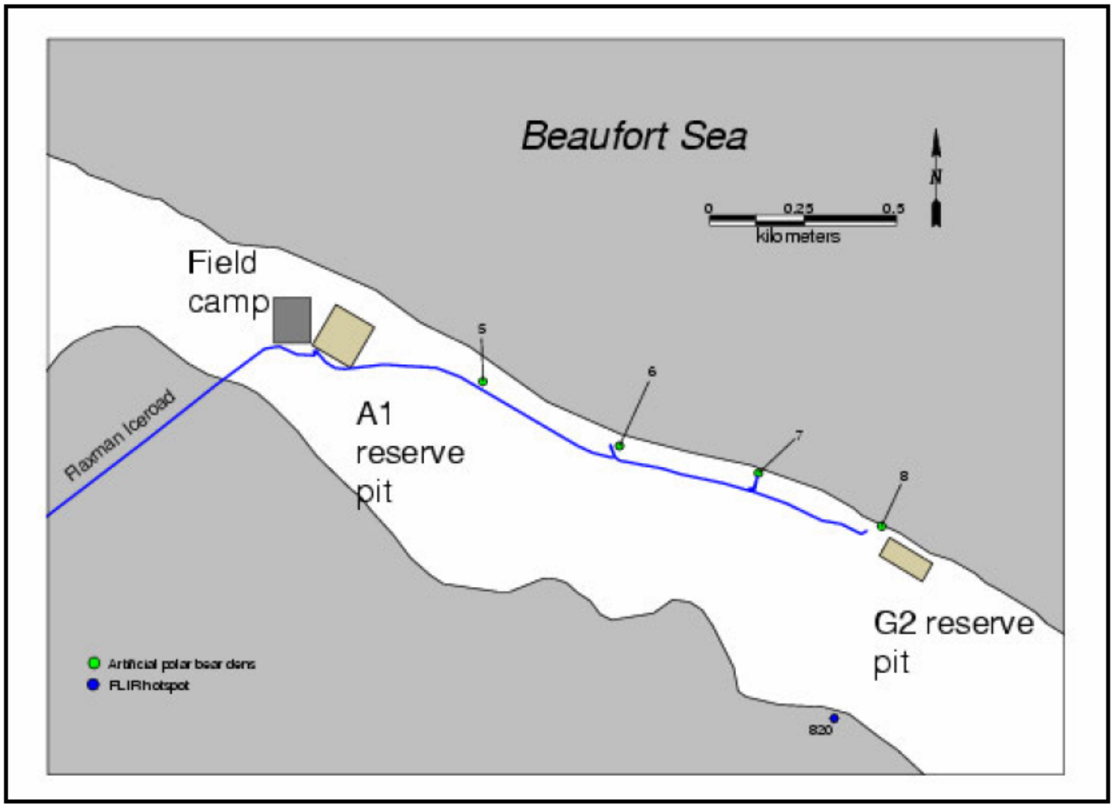

Figure 2. Map of the Flaxman Island field camp, with the reserve pit locations, artificial den sites, FLIR hotspots, and ice road.

Figure 3. Microphone and accelerometers (vibration transducers) deployed inside an artificial den. One vibration sensor is mounted in the tundra (background center); the other in the snow (right).

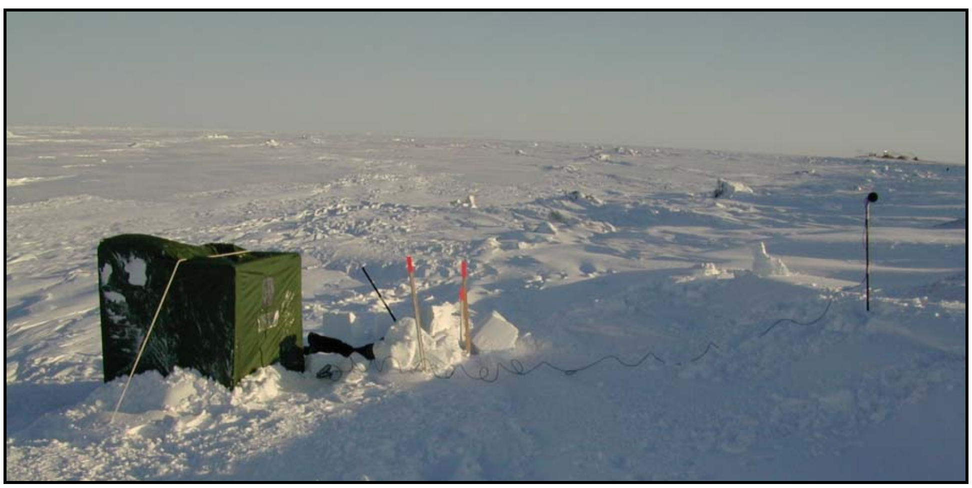

Figure 4: A den site before the snow walls were erected around the tent. The recording tent is on the left. The wooden stakes in the middle mark the entrance to the den. The in-air microphone is on the right.

Propane heaters were used to keep the interior temperature of the tent near 0° C. All den sites were manned by observers who operated the recording equipment and recorded observations and non-acoustic information.

From 1 to 8 March 2002 continuous airborne sound data and weather conditions at the construction camp on Flaxman Island were recorded. A sound level meter (Larson-Davis System 824) was connected to a calibrated microphone mounted outside one of the camp trailers and recorded, slow, fast and impulse time-weighted sound levels, flat frequency-weighted sound levels, and maximum peak pressure at 15-second intervals. The weather station (Davis Weather Wizard) was located at a different trailer, had wind and temperature sensors mounted atop a 7-meter high antenna, and recorded temperature, mean wind speed, and mean wind direction at 15-second intervals. Data from these two devices were downloaded daily to a laptop computer.

3.1.2.1 In-Air Sound Measurements

Two microphones (Larson-Davis Model 2540 free-field microphones with flat frequency response between 4 Hz and 40 kHz) were placed at each den site, one inside the den and one outside. The in-den microphone was mounted on a wooden board placed on the floor of the den. The outside microphone was mounted on an iron stand driven into the snow within a few meters of the den, pointing in the direction of the sound source (i.e., towards the tundra ice road or the reserve pit). Foam-ball wind covers were placed over the microphones to reduce wind noise in the sound recordings.

The outside and in-den microphones were connected via cables to programmable audio amplifiers (Larson-Davis Model 2200C) inside the equipment tents (Figure 5). Audio signals from the amplifiers were fed to professional digital audio recorders (Marantz PMD690; 16-bit, two-channel). The audio signals were digitized at sampling rates of 48 kHz per channel and stored directly on 340 Mb IBM Microdrives, which held approximately 32 minutes of two-channel digital-audio recordings. Recordings were then transferred to notebook computer hard drives for longer-term storage, and were backed-up on CD-R. Nearly continuous recordings were achieved using pairs of Microdrive disks at each site, which

Figure 5: Recording equipment setup inside one of the tents. At top left is the 2-channel microphone power supply/amplifier. Below it is the 8-channel accelerometer amplifier (only 6 channels used). The laptop computer in the center hosts the 16-channel Quatech digitizer used to record 6 channels of accelerometer data. At the right of the computer is the Marantz digital audio recorder.

were exchanged when full and downloaded to the laptop. All acoustic recording systems were calibrated using Larsen Davis Precision Acoustic Calibrators.

3.1.2.2 Ground Vibration Measurements

Two sets of tri-axial accelerometers (PCB Model 393A03) were placed inside each den; one was mounted in the tundra and the other in the snow of the den floor. Mechanical coupling for the snow-mounted accelerometer was improved by adding water to the snow surrounding the spike. Tri-axial accelerometers were constructed by mounting three single-axis transducers on a ground-coupling metal spike (Figure 6). In order to access the tundra we excavated through the snow of the den floor, or an area nearby if excavating through the den was not possible. This approach was used to measure differences in vibration levels experienced by a bear when the den floor is either in, or not in direct contact with tundra or sea ice. Accelerometer sensitivity was 1000 mV/g with a flat frequency response between 0.5 Hz and 2.0 kHz. The signals from the six individual accelerometer transducers at each den were fed via cables to one of two different models of PCB ICP power supply/amplifiers. Two den sites used single 8-channel PCB Model 482A20 programmable gain amplifiers, and two used pairs of 4-channel Model 482A05 unity-gain amplifiers. The amplifier outputs were fed to data acquisition cards (Quatech DAQP-16; 16-bit by 16-channel) installed in notebook computers. Custom software (JASCO Research Ltd., Victoria, British Columbia) was used to acquire the six channels of accelerometer data directly to a computer hard drive at a sampling rate of 16384 Hz for each channel. The accelerometer recording systems were calibrated in the lab immediately prior to deployment in the field.

Figure 6. Tri-axial accelerometer (vibration transducer) arrangement and ground coupling mounting spike.

3.2 Data Analysis

3.2.1 Acoustic Noise Metrics

The sound pressure levels (SPL), in decibels (dB), presented in this report are the time-weighted average levels computed according to ANSI S1.4-1983 (ANSI 1990):

$$SPL_{\tau}(t) = 10\log_{10}\left(\frac{1}{\tau}\int_{-\infty}^{t}\exp\left(-\frac{t-t'}{\tau}\right)\left(\frac{p(t')}{p_{\mathrm{ref}}}\right)^{2} dt'\right), \qquad (1)$$

where $p(t)$ is the time-varying pressure, τ is the time weighting period in seconds, and p_{ref} is the reference pressure standard 20 µPa in air. The three time-weightings used in this report are slow (τ = 1 s), fast (τ = 125 ms) and impulse (τ = 32 ms: ANSI 1990). The selection of time weighting normally depends on the duration of the in-air noise being measured. Continuous noise is generally gauged using slow time weighting, transient noises using fast weighting, and impulsive noise such as blast sounds by fast or impulsive weighting.

Equation 1 is appropriate for computing broadband sound levels. This report presents both broadband 1-octave sound levels and 1/3-octave band sound levels. Third-octave levels were computed by band-pass filtering, using standard 1/3-octave filters, prior to application of Equation 1 (Kinsler et. al. 1982).

All sound pressure levels presented in this report are flat frequency weighted (unity weight at all frequencies). Frequency weighting networks are sometimes applied to place more emphasis on frequencies for which the human ear is more sensitive. These would not necessarily have been appropriate for estimating impacts on polar bears. The most common frequency weighting function, A-weighting, substantially discounts energy at frequencies less than 200 Hz. It de-emphasizes the spectrum at 200 Hz by –10 dB, and at 20 Hz by –50 dB. We note that the frequency spectra of sounds measured during this project were dominated by low frequency energy. Consequently, the SPL levels presented in this report can be expected to be higher than similar A-weighted measurements published elsewhere.

3.2.2 Ground Vibration Metrics

Ground vibrations caused by vehicles and blasts propagate away from the source as seismic waves. While sound waves propagate by particle motion parallel to the direction of motion, ground vibration waves propagate with particle motion both parallel (referred to as longitudinal or primary-P waves) and perpendicular to the direction of propagation (referred to as shear, transverse or secondary-S waves). Furthermore, a third class of waves, referred to as, surface waves, propagate along interfaces between substrates of differing density. The two fundamental types of surface waves are Rayleigh waves and Love waves. Love waves require a bounded layer and are not important for the present case. Rayleigh waves, however, can propagate along the ground/snow – atmosphere interface with rotational particle displacement in the vertical and longitudinal plane. P waves generally propagate faster than S and Rayleigh waves. This effect is very evident in the ground vibration measurements made during this project. The faster longitudinal waves arrive first, followed by the nearly simultaneous arrivals of S and Rayleigh waves. The two latter arrivals are distinguished by the fact that Rayleigh waves have no transverse component (Bollinger 1971). The blast measurements clearly exhibit wave arrivals with strong longitudinal and vertical components, but present a weak transverse component.

Ground vibration is quantified by measuring real ground movement in three orthogonal planes. This measurement can be made using geophones, which measure ground velocity, or accelerometers, which measure acceleration. Measurements made by either type of device can be used to derive the three common metrics: ground displacement, ground velocity, and ground acceleration. Ground velocity and acceleration are the more commonly referenced metrics. We present all three metrics in this report. Tri-axial accelerometers were used for the present study. The three individual accelerometers comprising each tri-axial sensor were oriented in planes referred to as longitudinal, *L* (pointing towards the noise source), transverse, *T* (pointing 90° from the noise source), and vertical, *Z*. The acceleration vector was computed from the vector sum of the three orthogonal axial components. However, most metrics associated with vibration consider only the amplitude of acceleration as a function of time, $a(t)$, given by Equation 2.

$$a(t) = \sqrt{a_L(t)^2 + a_T(t)^2 + a_Z(t)^2} \tag{2}$$

The velocity component of amplitude, $v_x(t)$, and the displacement component of amplitude, $d_x(t)$, were computed from the acceleration component data through simple integration, as shown in Equations 3 and 4,

$$v_x(t) = \int_{-\infty}^{t} a_x(t')\,dt' \tag{3}$$

$$d_x(t) = \int_{-\infty}^{t} v_x(t')\,dt' \,, \tag{4}$$

where *x* represents the component (*L*, *T* or *Z*). The total acceleration amplitude was computed from the measured tri-axial acceleration components using Equation 2. Velocity and displacement amplitudes were obtained by applying functions equivalent to Equation 2, to the derived velocity and displacement components from Equations 3 and 4, respectively.

3.2.3 Computation Procedures

All acoustic and vibration data collected at the den sites were stored as time-stamped, 16-bit, raw digital waveforms. The waveform data were processed using custom software (JASCO Research Ltd., Victoria, British Columbia).

Time-weighted average (TWA) sound pressure levels were computed according to Equation 1[1]. Sound levels in broadband sound levels 1-octave and 1/3-octave bands were calculated by applying digital band-pass filters to the raw waveform data prior to applying Equation 1. In some cases, additional digital filtering was applied to selectively remove low-frequency (<20 Hz) wind noise and high frequency (>10 kHz) electrical noise from the data. The exact characteristics of these additional filtering operations are specified on a case-by-case basis.

The spectral energy content of sounds produced by the well casing blast and the back-up beeper were computed by applying Fast Fourier Transforms (FFT) to the respective data. The results of these analyses are presented in plots that show the frequency distribution of the energy produced by these sound sources, expressed in decibels per Hz.

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[1] The infinite time-window of Equation 1 is not realizable in practice. Therefore, a finite time-window, containing 99% of the weighting function's area, was used for the numerical calculation.

Ground velocity and displacement were computed from the acceleration data using Equations 3 and 4. Vibration data were band-pass filtered between 4 Hz and 1 kHz to eliminate high and low frequency electrical noise. Vibration amplitudes were computed by applying Equation 2. For continuous vibrations, such as those produced by machinery or vehicles, the vibration amplitudes were smoothed using the exponential time weighting function of Equation 5.

$$\overline{a}(t) = \int_{-\infty}^{t} a(t')\, e^{-(t-t')/\tau}\, dt' \qquad (5)$$

A time constant of τ = 125 ms was used for this smoothing.

3.3 Noise and Vibration Sources

From 5 to 8 March 2002 we collected acoustic and ground vibration data resulting from remediation activities on Flaxman Island. Additionally, on 7 March we collected acoustic and ground vibration data during experimental trials involving operating tracked vehicles on the ice road and in the snow and helicopter overflights and maneuvers.

3.3.1 Monitoring Industrial Activities

Sound and vibration levels from normal industrial activities were monitored continuously at all four den sites for at least six hours each day. Field personnel logged observations regarding the timing, location, and duration of the activities during the recordings.

3.3.1.1 Excavation at G-2 Pit

Measurements of noise and ground vibration were made during normal operations of heavy equipment in the G-2 reserve pit. Heavy equipment within the pit included, but was not limited to, trucks, graders, front-end loaders, a bulldozer, and a trimmer. Activities included, but were not limited to scraping the pit, stockpiling debris, and loading Kenworth Maxihauls (gravel hauling trucks) with muds and cuttings. Additionally, we measured the noise from the reverse gear (backup) beeper from a front-end loader, at a range of approximately 50 meters.

Recordings were made of the overall excavation noise from the G-2 pit over five minutes during both an active (i.e., multiple pieces of heavy equipment operating simultaneously) and nonactive period (i.e., equipment engines idling). Sound level computations were performed using slow time weighting and flat frequency weighting above 11 Hz. Wind noise below 11 Hz was filtered from the acoustic data.

3.3.1.2 Ground Vehicles

Ground vehicles monitored during this study included empty and loaded gravel haulers, a front-end loader, pick-up trucks, a fuel truck, and two types of all-terrain tracked vehicles (described under "experimental trials"). Noise level and ground vibration measurements were made as these vehicles approached and passed all four den sites along the ice road connecting pits A-1 and G-2, although data from only one or two dens are presented in this report for brevity.

3.3.1.2.1 Gravel Haulers

Kenworth Maxihauls were used at the Flaxman Island site for transporting gravel away from the excavation pits. The Maxihauls have a 30 cubic yard capacity and weigh about 70,000 lbs empty and

140,000 lbs. loaded. On 5 March, sound and vibration data were recorded for a pair of Maxihauls, both empty and loaded, traveling along the Flaxman Island ice-road.

Vehicle distance from the den sites was interpolated from logged positions of the trucks. Four empty and two full gravel haulers were traveling at a mean speed of about 18 kph (11 mph).

Acoustic data from gravel haulers were band-pass filtered between 22 Hz and 354 Hz to isolate truck noise from other noise sources in the data (i.e., wind and walking observers). Noise was eliminated from the vibration data by band-pass filtering between 8 Hz and 1 kHz.

3.3.1.2.2 Front-end Loaders

Front-end loaders (John Deere model 744H) were used at the Flaxman Island site for moving snow and gravel and loading the gravel haulers. Sound and vibration measurements were made for a front-end loader traveling along the Flaxman Island ice road at a speed of 22 kph (14 mph). Acoustic data from front-end loaders were band-pass filtered between 22 Hz and 1.4 kHz to isolate vehicle noises. Vibration data were band-pass filtered between 8 Hz and 1 kHz.

3.3.1.2.3 Pick-up Truck

Standard 1-ton pickup trucks (typically crew-cab models) were used routinely to transport personnel and equipment along the ice road. Noise and ground vibration measurements were made for a pickup truck traveling along the Flaxman Island ice road at a speed of 32 kph (20 mph). Acoustic data from pick-up trucks were band-pass filtered between 22 Hz and 707 Hz to isolate vehicle noise. Ground vibration data were band-pass filtered between 8 Hz and 1 kHz.

3.3.1.2.4 Fuel Truck

Noise measurements were made for a 4000-gallon Ford L3000 fuel truck traveling along the Flaxman Island ice-road at a mean speed of about 17 kph (10 mph). Acoustic data from fuel trucks were band-pass filtered between 11 Hz and 252 Hz to isolate vehicle noise.

3.3.1.3 Blasting Activities

On 8 March, noise and vibration data was recorded during the detonation of explosives used to sever the well pipe at Flaxman Island (see Appendix A, Figure A-1). Additionally, a recording system was set up at the construction camp to measure sound levels and the acoustic waveforms from a position much closer to the detonation than the dens. This activity was part of the plugging and removal of the wellhead. The cutting charge, detonated 19 m underground, was 8.7 kg of liquid nitromethane chemically sensitized with diethylenetriamine (DETA). The TNT weight equivalence for this explosive was approximately 1:1. The wind speed at the time of the detonation was 5 kph (3.0 mph) from 300-320^{o}.

The acoustic recordings of the blast were impulse time weighted and flat frequency weighted. Vibration data were digitally filtered between 4 Hz and 1 kHz.

3.3.2 Experimental Trials

During experimental trials we attempted to control the location of operation for the tracked vehicles and helicopters to allow data collection at close distances to the dens. Otherwise our intent was to allow the equipment operators to run the vehicles as they would under normal circumstances.

3.3.2.1 Tracked Vehicles

On 6 March, vibration and acoustic data were recorded for two-tracked vehicles, the Hägglunds BV206 and the Tucker Sno-Cat. The Hägglunds BV206 is a tracked vehicle used to transport personnel and equipment in the arctic. The vehicle can travel at a top speed of 50 kph (31 mph) over hard ground, and 35 kph (22 mph) in deep snow. However, average personnel transport speeds are typically 8-16 kph (5-10 mph) over uneven terrain. The Tucker Sno-Cat is used similarly to the Hägglunds tracked vehicle for personnel and supply transport.

Sound and vibration data were obtained at Den 5 and Den 7 as a Hägglunds tracked vehicle followed a path along the Flaxman Island ice road and then back parallel to the road on the snow-covered tundra (mean speed = 24 kph). The closest point of approach to a den was 18 m (Den 5).

Another tracked vehicle, a Tucker Sno-Cat followed a path similar to the Hägglunds', at a mean speed of 18 kph. Tracked vehicles were operated, as they would be under normal operating conditions in the arctic. Paths for both vehicles were tracked using an on-board GPS receiver. Vehicle distance from sound and vibration receivers were calculated from logged GPS coordinates along the vehicle's path. The mean wind speed and direction at the time of recording was 13 kph (8 mph) from 180^o and 11 kph (7 mph) from 180^o for the Hägglunds and Tucker, respectively.

Sound level computations for the two-tracked vehicles were performed with slow (1 second) time weighting and flat frequency weighting. Wind noise below 11 Hz was filtered from the acoustic data. Noise was removed from the vibration data by applying a band-pass filter between 8 Hz and 1 kHz.

3.3.2.2 Helicopter Overflights

On 7 March, acoustic data were recorded at all four den sites simultaneously during overflights by a Bell 206 Jet Ranger and Bell 212 helicopter. Additionally, the helicopters performed a variety of maneuvers near Den 6, which included fly-bys, hovers, take-offs, and landings. Onboard GPS receivers logged flight paths. We recorded the approach vector and altitude of the helicopters during maneuvers. A laser range finder was used at Den 6 to determine the altitude of the helicopter during the fly-by and hovering activities. In addition, we recorded the timing of the helicopter maneuvers at each den site. Acoustic data were high-pass filtered above 11 Hz and 6 Hz to remove wind noise from the recordings from the Bell 206 and Bell 212, respectively. The wind speed at the time of recordings was 32 kph (20 mph) from 180^o.

4 RESULTS

A large amount of high-quality noise and vibration data were collected during the field period (approximately 30 hours, each from 4 den sites). Nearly continuous weather and ambient in-air noise data were collected from the camp near A-1 (Figure 1) from 1-8 March 2002. Preliminary analyses were carried out on all data. However, not all data could be analyzed in sufficient detail for presentation in this report. In some cases, only data from one or two of the four den sites are presented. In these cases, the preliminary results from the omitted sites indicated good consistency with those sites presented.

4.1 Industrial Activities

4.1.1 Excavation Activities at G-2 Pit

Recordings were made of the overall excavation noise from the G-2 pit over five minutes during both a high activity (Figure 7, Table 2) and a low-activity period (Figure 8, Table 3). During the low-activity period, most of the machinery was left idling, so engine noise and associated vibration were still present. During the high-activity period, median broadband sound levels (Table 2) peaked at 83.8 dB re 20 µPa in-air and 54.0 dB inside Den 8 (29 dB den attenuation; 76 m from the pit) and dropped 20.0 dB in-air to 63.8 dB at Den 7 (416 m from the pit). Median in-den sound pressure level at Den 7 was 37.7 dB, an attenuation of 26.1 dB. Median in-air sound pressure levels increased to 73.0 dB at Den 5, 1,190 m from the active pit, but in-den pressure levels continued to decline to 31.0 dB. Den 5, was 1,190 m from G-2 pit, but only 504 m from the A-1 site where the housing camp and associated machinery were located.

In-den spectral distribution generally followed the in-air distribution for Dens 7 and 8, and were predominated by low-frequency sounds (Figure 7). Den 8 was characterized, both in-air and in-den, by a strong spike in pressure at 60 Hz, with diminishing pressure at higher frequencies. Den 7 also showed a small peak at 60 Hz, but the higher frequencies dropped off faster than for Den 8. Dens 5 and 6, further from the active pit, did not follow this pattern as closely, and their in-den spectral distributions were flatter across frequencies.

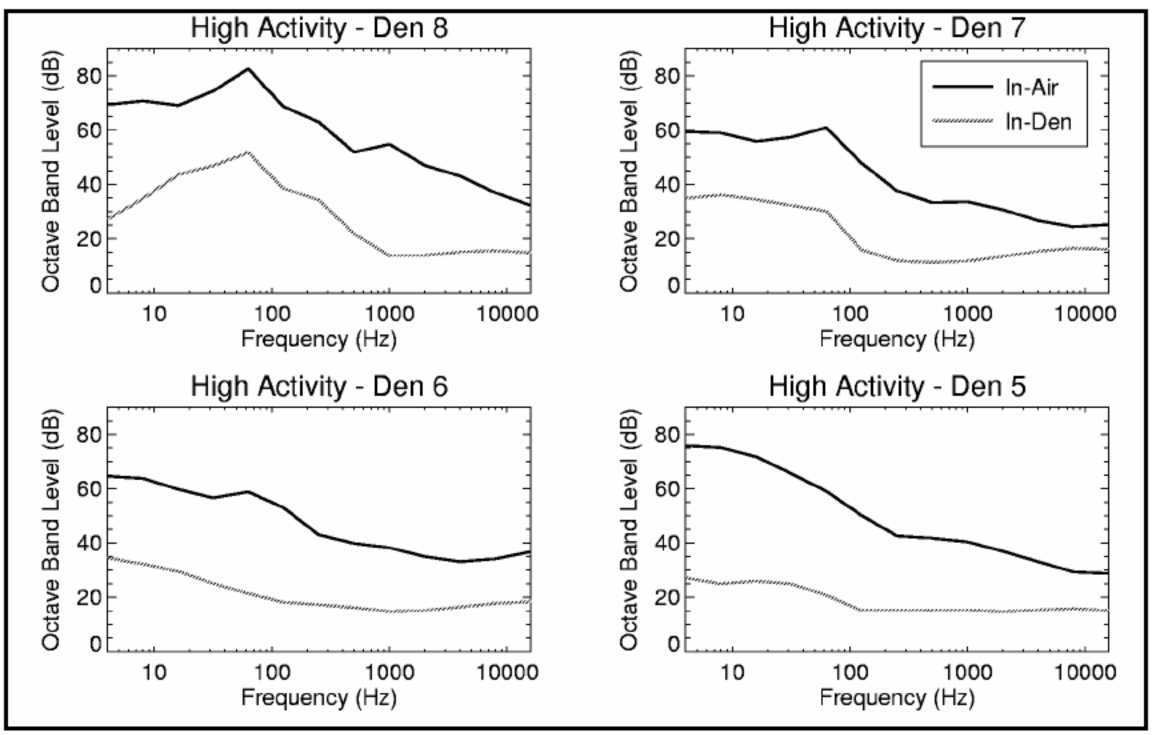

Figure 7: Octave bands levels (dB re 20 µPa) for high activity at the pit. Frequency axes are logarithmic. Results are medians of 0.5 second intervals over a 5 minute period.

Table 2: Median broadband sound pressure levels (dB re 20 µPa) recorded during a 5-minute interval of high activity at pit G-2. Distances are quoted to the center of the reserve pit.

		Median Broadband Sound Level (Slow) (dB re 20 µPa)	
Recording Site	Distance to Pit (m)	In-Air	In-Den
Den 8	76	83.8 ± 1.7	54.0 ± 1.8
Den 7	416	63.8 ± 2.0	37.7 ± 1.7
Den 6	807	64.0 ± 1.7	32.5 ± 0.7
Den 5	1190	73.0 ± 2.5	31.0 ± 2.4

During the low-activity (idle) period, median in-air broadband sound levels (Table 3) were highest at Dens 8 (76.3 dB) and 5 (74.6 dB). In-snow broadband levels for these dens were 45.7 dB and 32.5 dB, respectively (Table 3). The median in-air and in-den sound pressure levels at Den 8 were approximately 7.5 dB and 8.3 dB lower during the low-activity period than the high-activity period. In contrast, the in-air and in-den median sound pressure levels were 1.6 dB and 1.5 dB higher at Den 5 during the low-activity period than the high-activity period likely related to the close proximity of camp.

During the idle period, the spectral distribution of noise at Den 8 was again dominated by low frequency sounds, with a drop in pressure for frequencies higher than 100 Hz. The in-den noise showed a strong peak between 10 and 100 Hz, with pressures relatively flat from 100 Hz to 10,000 Hz. (Figure 8). Den 7 did not show the peak at 100 Hz during the low-activity period as it had for the high-activity period. The spectral distributions of Dens 5 and 6 during the low-activity period are very similar to those during the high-activity period, indicating little influence of exposure to industrial activities at G-2.

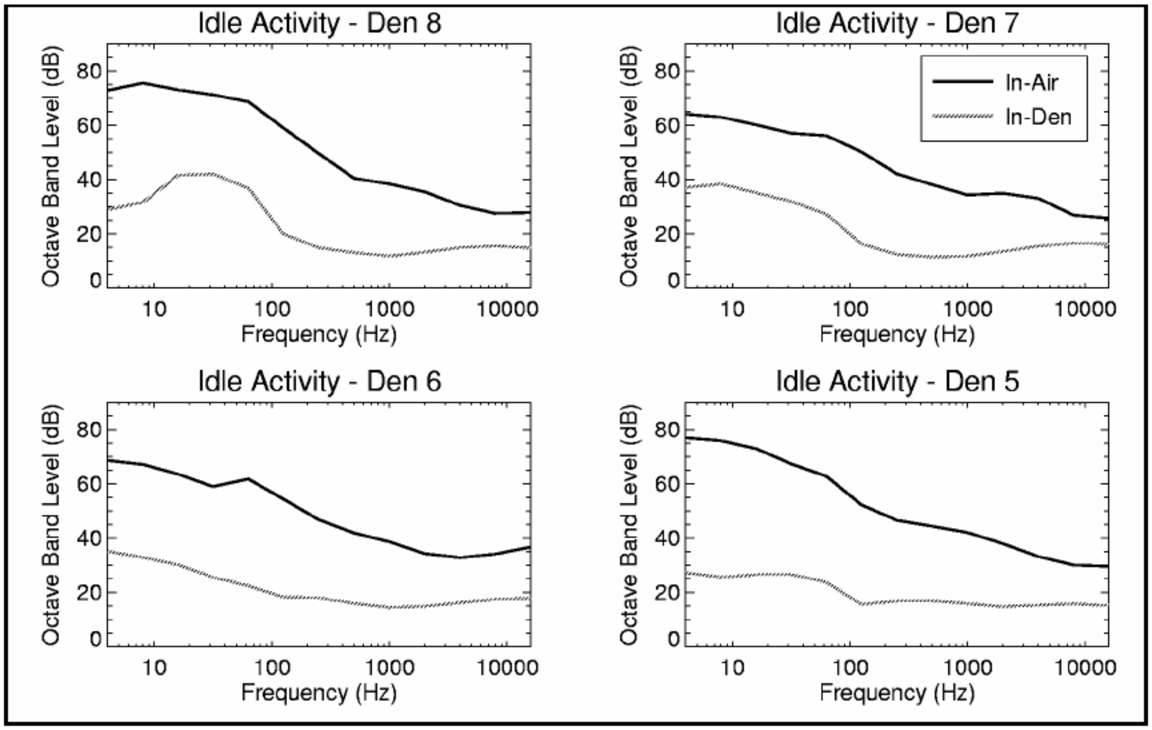

Figure 8: Octave bands levels (dB re 20 µPa) during an idle period. Frequency axes are logarithmic. Results are medians of 0.5 second intervals over a 5 minute period.

Table 3: Median broadband sound pressure levels (dB re 20 µPa) recorded during an interval of 5 minutes during an idle period. Distances are quoted to the center of the pit.

		Median Broadband Sound Level (Slow) (dB re 20 µPa)	
Recording Site	Distance to Pit (m)	In-Air	In-Den
Den 8	76	76.3 ± 1.2	45.7 ± 0.8
Den 7	416	63.4 ± 1.3	37.6 ± 1.5
Den 6	807	67.2 ± 1.8	33.0 ± 1.1
Den 5	1190	74.6 ± 1.8	32.5 ± 2.9

4.1.1.1 Trimmer Operation

A loader-mounted soil-stripping trimmer, operating at G-2 pit, was recorded from Den 8. A representative segment of these data is shown graphically in (Figure 9). The trimmer starts operating 40 seconds into the plot. Acceleration in the snow increased from approximately 1.5 mm/s^2 before operation to a peak of nearly 5 mm/s^2 during trimmer operation (Figure 9). Velocity and displacement of both snow and tundra also show similar peaks after trimmer operations began.

Mean tundra acceleration increased from 0.57 mm/s^2 before operations to 1.18 mm/s^2 during operations (Table 4). Velocity and displacement in tundra and in snow were very similar before and during the operation of the trimmer.

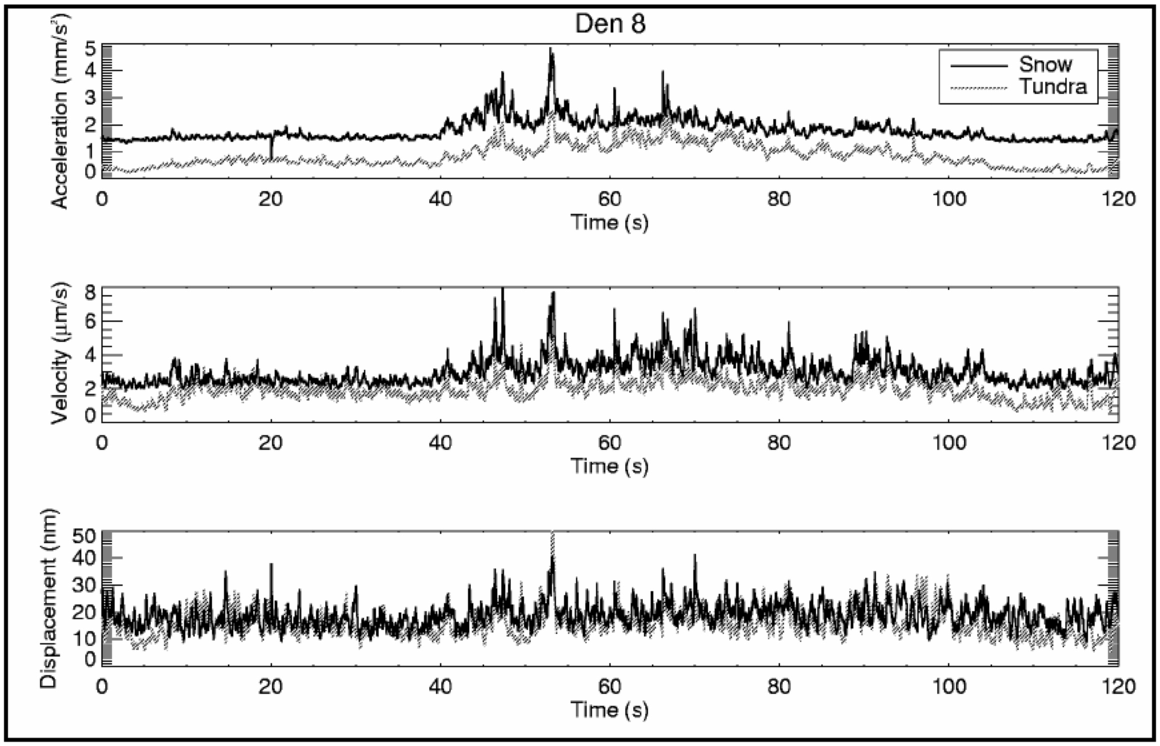

Figure 9: Ground vibration levels from a trimmer in the G-2 reserve pit, measured at Den 8. The trimmer begins operating at the 40-second mark.

Table 4: Mean ground vibration levels (± standard deviation) before and during operations of a trimmer in the G-2 reserve pit, measured at Den 8.

Vibration Metric	Before start of grinder	During grinder operation
Acceleration (tundra)	0.57 ± 0.13 mm/s^2	1.18 ± 0.34 mm/s^2
Acceleration (snow)	1.52 ± 0.08 mm/s^2	2.07 ± 0.42 mm/s^2
Velocity (tundra)	1.73 ± 0.44 μm/s	2.26 ± 0.56 μm/s
Velocity (snow)	2.49 ± 0.30 μm/s	3.50 ± 0.81 μm/s
Displacement (tundra)	14.7 ± 4.0 nm	17.4 ± 5.3 nm
Displacement (snow)	17.0 ± 3.8 nm	20.3 ± 4.6 nm

4.1.1.2 Beeper Noise

The noise from the reverse gear (backup) beeper from a front-end loader operating in the G-2 pit was recorded at Den 8, at a range of about 50 meters. The pulses last approximately a third of a second and have a strong tone (dominant at 1000 Hz) accounting for most of the sound energy (Figure 10). Sound levels outside the den clearly showed the pulses with sound pressure levels peaking near 70 dB, while inside the den the pulses are not detectable from background noise (Figure 11). The insulating properties of the den for higher frequency sound are quite apparent.

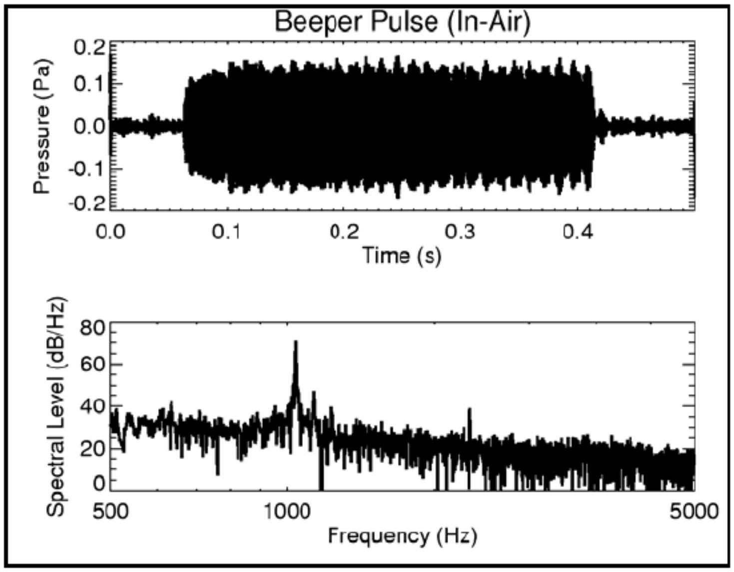

Figure 10: Pressure waveform and spectrum of a single pulse of the backup beeper on a front-end-loader, recorded at short range. Frequency axis is logarithmic.

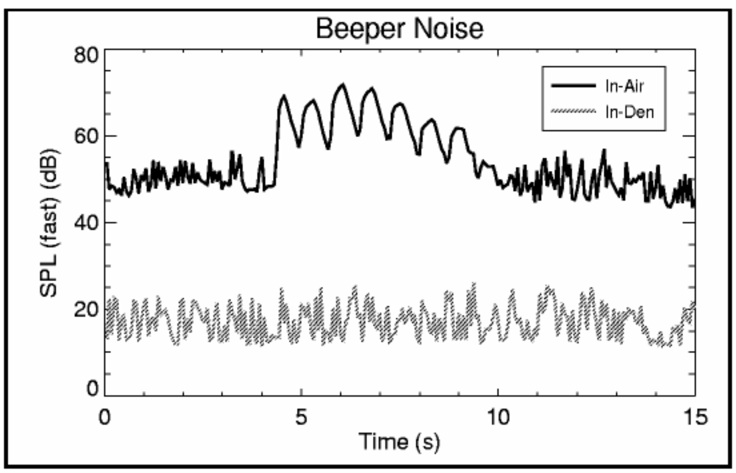

Figure 11: Sound pressure levels (fast time weighting in dB re 20 µPa) from a series of backup beeper pulses, recorded at short range (approx. 50 m at Den 8). Sound pressure levels were calculated with fast time weighting in an octave band centered at 1000 Hz (0.7–1.4 kHz).

4.1.2 Ground Vehicle Recordings

Sound and vibration data were recorded for empty and loaded Kenworth Maxihaul gravel haulers, a John Deere 744H front-end loader, standard 1-ton pickup trucks, and a Ford L3000 fuel truck while vehicles were conducting normal operations (Table 5, Table 6). Since vehicles were conducting normal operations, we were unable to control for vehicle speed or other parameters; however, these results give the best estimation of actual vehicle use and the resulting sound levels that polar bears in dens might be exposed to.

Table 5: Received sound pressure levels (SPL; re 20 µPa) and distances of closest point of approach (CPA) of vehicles at Dens 5 (D5) and 7(D7). Separate values for Range to Background are provided where significant difference was noted between the two dens.

Vehicle	Speed (kph)	CPA (m)	In-den SPL at CPA (dB)	Outside den SPL at CPA (dB)	In den SPL background (dB)	In-Den Range to Background (m)
Gravel Hauler (Empty)	18	12	47	84	30	D5-500 D7-2000
Gravel Hauler (Loaded)	19	12	48	87	30	500
Front End Loader	22	12	43	81	27	500
Pick-up truck	32	12	37	71	25	100
Fuel truck	17	12	50	80	29	300
Hägglunds BV206	24	18	55	85	30	D5-400 D7-1000
Tucker Sno-Cat	18	20	38	80	27	400

Table 6: Vehicle ground vibration metrics and corresponding distances of closest point of approach (CPA) of all-terrain tracked vehicles.

Vehicle	Speed (kph)	CPA (m)	Ground acceleration at CPA (mm/s^2)	Snow acceleration at CPA (mm/s^2)	Snow velocity at CPA (µm/s)	Range to acceleration < .5 mm/s^2 (m)
Gravel Haul (Empty)	18	23	3.8	5.5	3.1	40
Gravel Haul (Loaded)	19	23	3.7	4.2	2.5	60
Front End Loader	22	22	8.0	8.5	3.5	60
Pick-up truck	32	22	1.5	1.5	1.3	43
Fuel truck	17	12	Data unavailable.			
Hägglunds BV206	24	18	10	11	13	90
Tucker Sno-Cat	18	20	1.2	1.5	1.9	30

Despite the use of microphone covers designed to reduce wind noise, continuous wind noise was prevalent in the acoustic recordings of vehicle operation made outside the dens, especially at frequencies below 20 Hz. Inside the dens, noise from observers walking around the sites was occasionally present above 500 Hz. Electrical noise, at frequencies greater than 10 kHz, was also present in recordings with high gain levels. It was necessary to filter data to remove energy below 11 Hz (or 20 Hz in the case of pickup trucks) to differentiate the noise from the vehicles from the background noise caused by the wind.

Broadband sound levels for vehicles 12-20 m from the recording den ranged from 37 to 55 dB re 20 µPa inside the dens (Table 5, Figure 12), and 71 dB to 87 dB re 20 µPa outside the dens. Background levels in dens ranged from approximately 25 dB re 20 µPa to 30 dB re 20 µPa. Noise from various vehicles attenuated to background levels at distances from approximately 40 m to more than 2,000 m. The Hägglunds tracked vehicle and the fuel truck produced the loudest sounds inside the dens, while the pickup truck and Tucker Sno-Cat were the quietest vehicles.

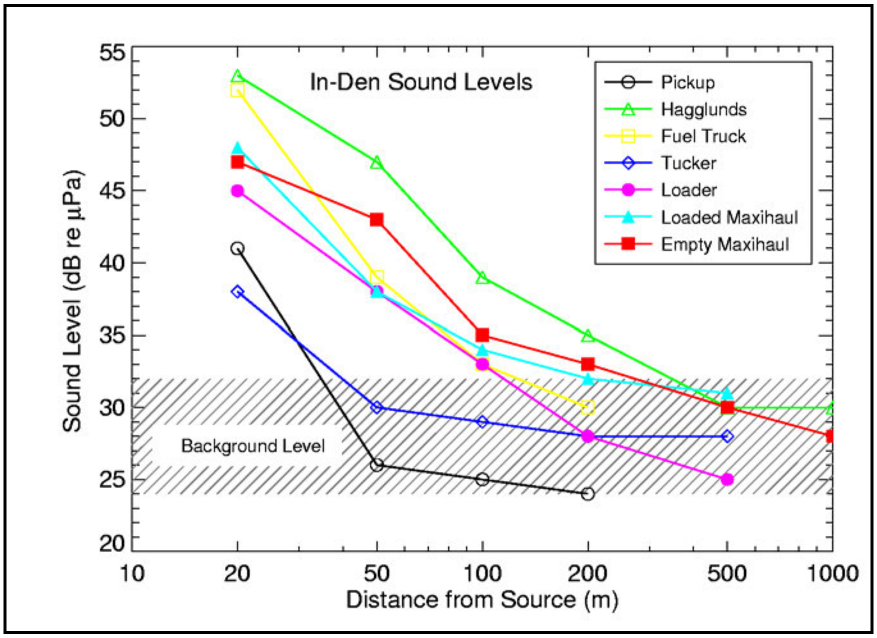

Figure 12. Broadband levels of in-den sound as a function of distance from source. The shaded background level refers to recorded ambient noise during the time of study. (Note: log scale for distance).

Ground and snow vibrations varied considerably for different vehicles. The Hägglunds tracked vehicle produced the maximum vibration in the snow, and the Tucker Sno-Cat tracked vehicle and pickup truck produced the least (Table 6). Vibrations in the snow, measured as velocity (Figure 13) were similar for all vehicles other than the Hägglunds at 50 m from the source, and were undetectable for all vehicles except the Hägglunds at 100 m. Snow vibrations from the Hägglunds were detectable to a range of 200 m.

Broadband vehicle traffic noise was reduced between 30 dB and 42 dB by the snow surrounding the artificial dens (Table 5). The loudest vehicle sounds received outside the dens was from the loaded gravel hauler at 87 dB, which was reduced to 48 dB in the den. The loudest vehicle sounds received from within the den was the Hägglunds, 55 dB, and was 85 dB outside the den. Vehicle noise inside the den was 11 dB to 25 dB above the ambient noise level.

Most vehicle noise was undetectable once the vehicles were 500 m from the den. However, the Hägglunds and the loaded gravel hauler were detectable in Den 7 when they were more than 500 m away; the Hägglunds was detectable to 1000 m and the full gravel hauler was detectable to 2000 m away from the den.

A comparison of the same vehicle (loaded Maxihaul gravel hauler) recorded as it approached and passed different dens shows that there was variation in received levels among dens (Figure 14). The in-air levels recorded at each den were similar, while there was a difference of approximately 15 dB for received levels within dens.

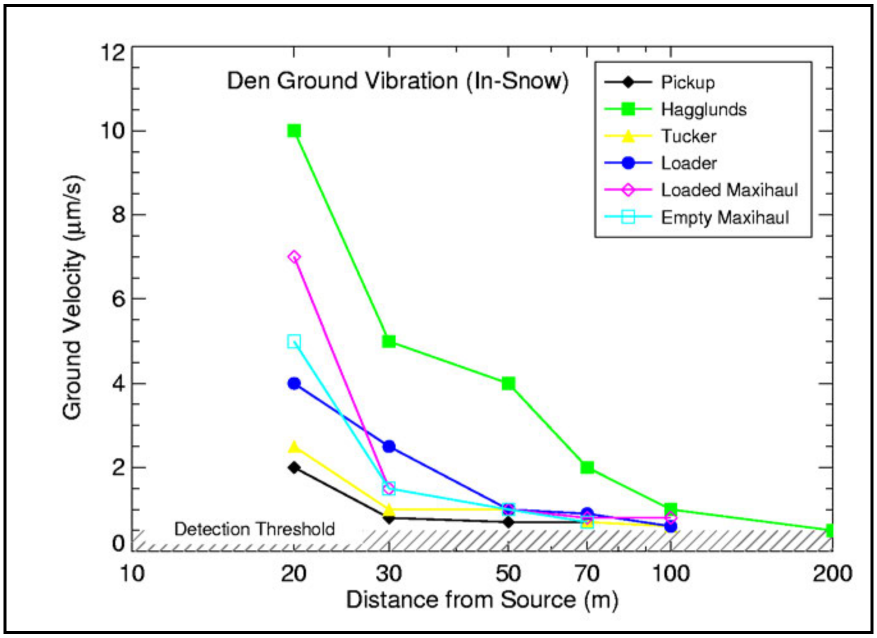

Figure 13. Den ground vibration (in snow) as a function of distance from source.

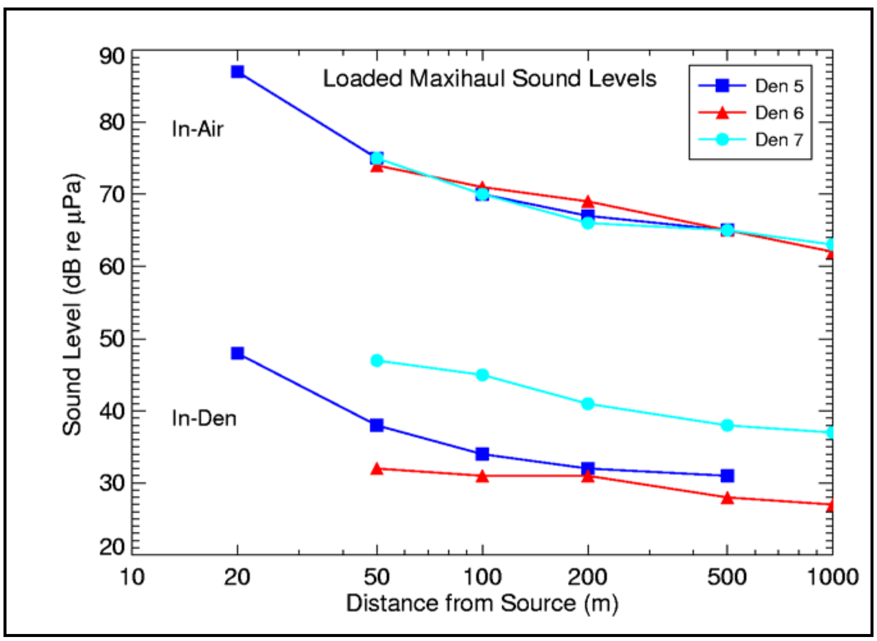

Figure 14. Broadband levels of in-air and in-den sounds from loaded haulers received at three dens as a function of distance from source.

Detailed descriptions of the sound and vibration for each vehicle are presented below.

4.1.2.1 Gravel Haulers

Kenworth Maxihauls were used at the Flaxman Island site for transporting gravel away from the excavation pits. Noise and vibration records for several Maxihauls, both empty and loaded, traveling along the Flaxman Island ice-road were obtained on 5 March.

Noise levels from the approach of a pair of empty Kenworth Maxihauls toward the excavation pit (G-2) are shown in (Figure 15). The empty gravel haulers were traveling at a mean speed of about 18 kph (11 mph) and the CPA was 23 m. The sound pressure level in air increased from approximately 60 dB at 1,000 m to 84 dB at 23 m from the Den. In the Den, the maximum SPL was 47 dB; a reduction of 37 dB compared with in-air measurements and 17 dB above the background level of 30 dB. Noise from the empty gravel hauler was indistinguishable from background noise at 500 m from Den 5 and 2,000 m from Den 7 (Table 5). The spectral distribution of the Maxihaul sounds is dominated by frequencies below 400 Hz (Figure 16). Sound pressure levels were approximately 30 dB lower in the dens for all frequencies.

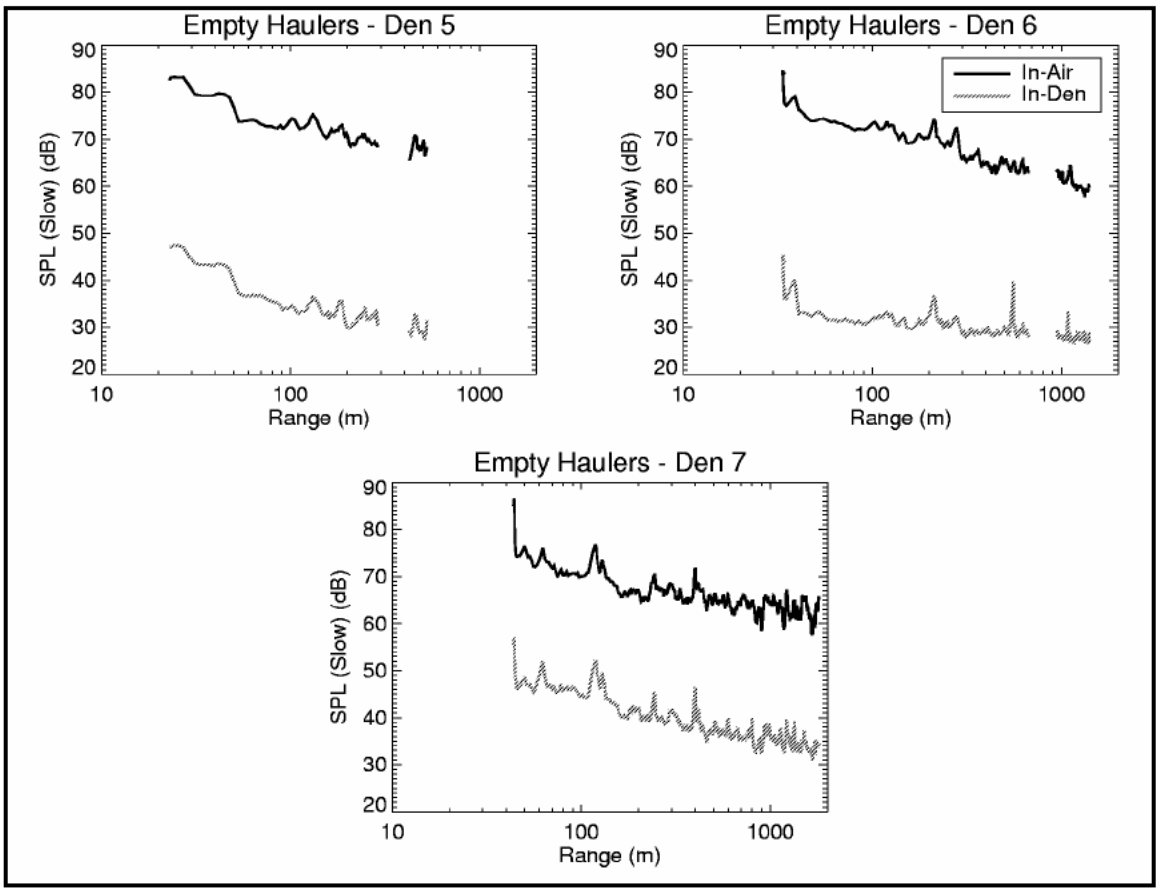

Figure 15: Broadband sound pressure levels (re 20 µPa) from the approach of a pair of empty gravel haulers. Range axes are logarithmic. Gaps indicate removal of spurious acoustic data not related to the gravel haulers.

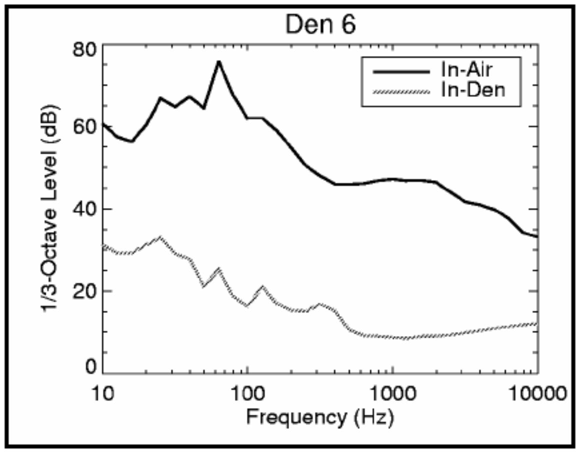

Figure 16: 1/3-octave band sound pressure levels (re 20µPa) from an empty Kenworth Maxihaul measured at a range of 34 meters from Den 6.

Vibration levels from the empty gravel haulers showed great variability (Figure 17). Gravel haulers were recorded as they approached and passed each station, resulting in the double lines seen in figure 17. Vibration levels from gravel hauler 2 and 3 (Figure 17) dropped very quickly to low levels, while haulers 1 and 4 had higher measurements for longer periods. Received levels from three of the four haulers shown in Figure 17 were nearly identical, suggesting that the vibration levels are more a function of distance from the station than of terrain, since the terrain was different on each side of Den 5. The vibration levels in the snow and the tundra are also very similar for the four haulers (Figure 17).

The noise levels from two individual passages of full Kenworth Maxihaul gravel haulers, as they left the excavation pit, are shown in figures 18 and 19. The two full gravel haulers were traveling at speeds of 19 kph (12 mph) and 16 kph (10 mph), respectively. Again, the approach and passing of the vehicles is responsible for the double lines in figures 18 and 19. The loaded gravel haulers were loudest in air and in dens at the CPA, the maximum SPL in air was 87 dB re 20 µPa, and was 48 dB re 20 µPa in the den (Table 5), a difference of 39 dB. The den background noise was 30 dB, and noise from the full gravel hauler diminished to background levels within the den at a range of 500 m (Table 5).

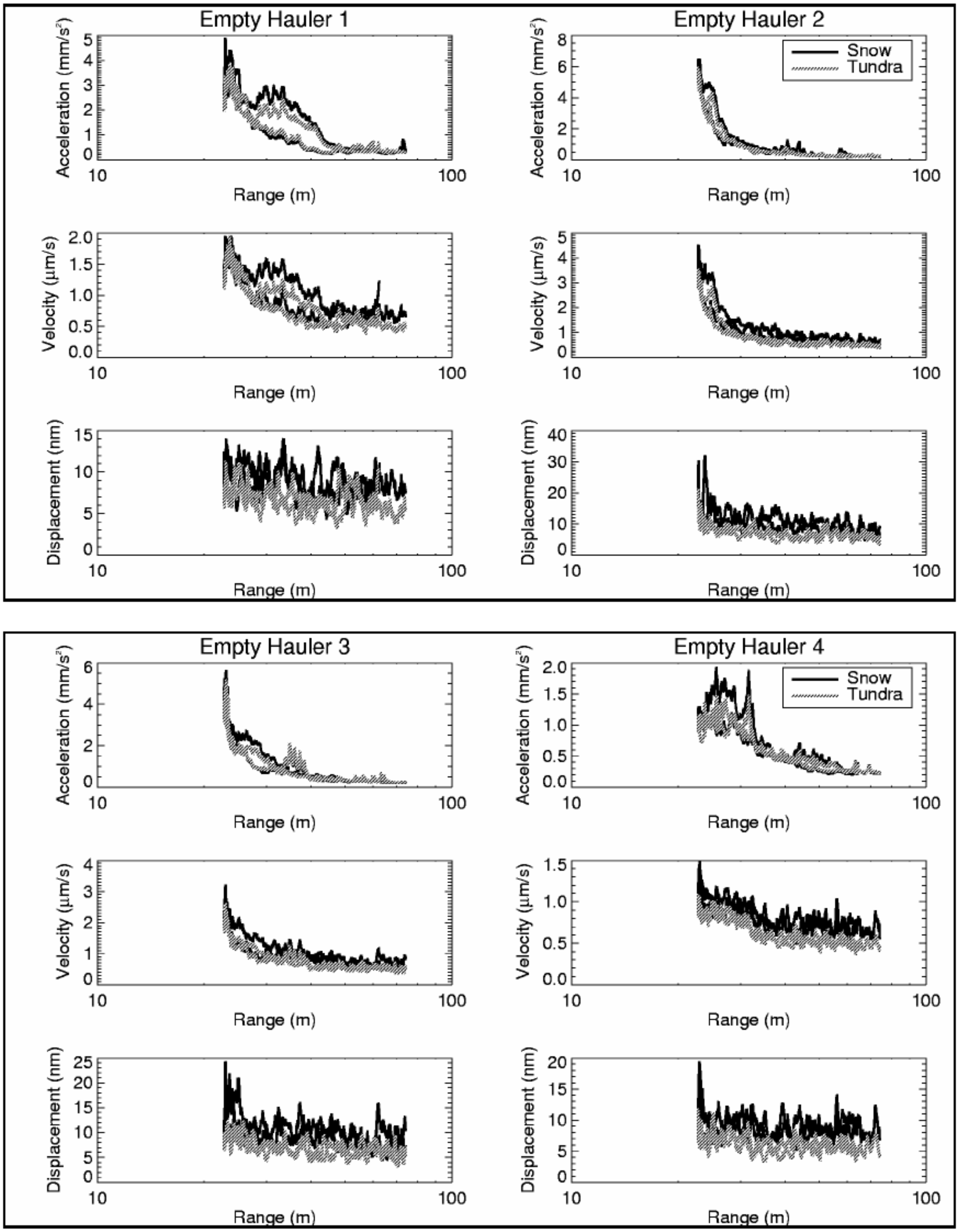

Figure 17: Vibration levels from the approach and passage (double lines) of four empty gravel haulers. Vibration records are from the Den 5 site. Range axes are logarithmic.

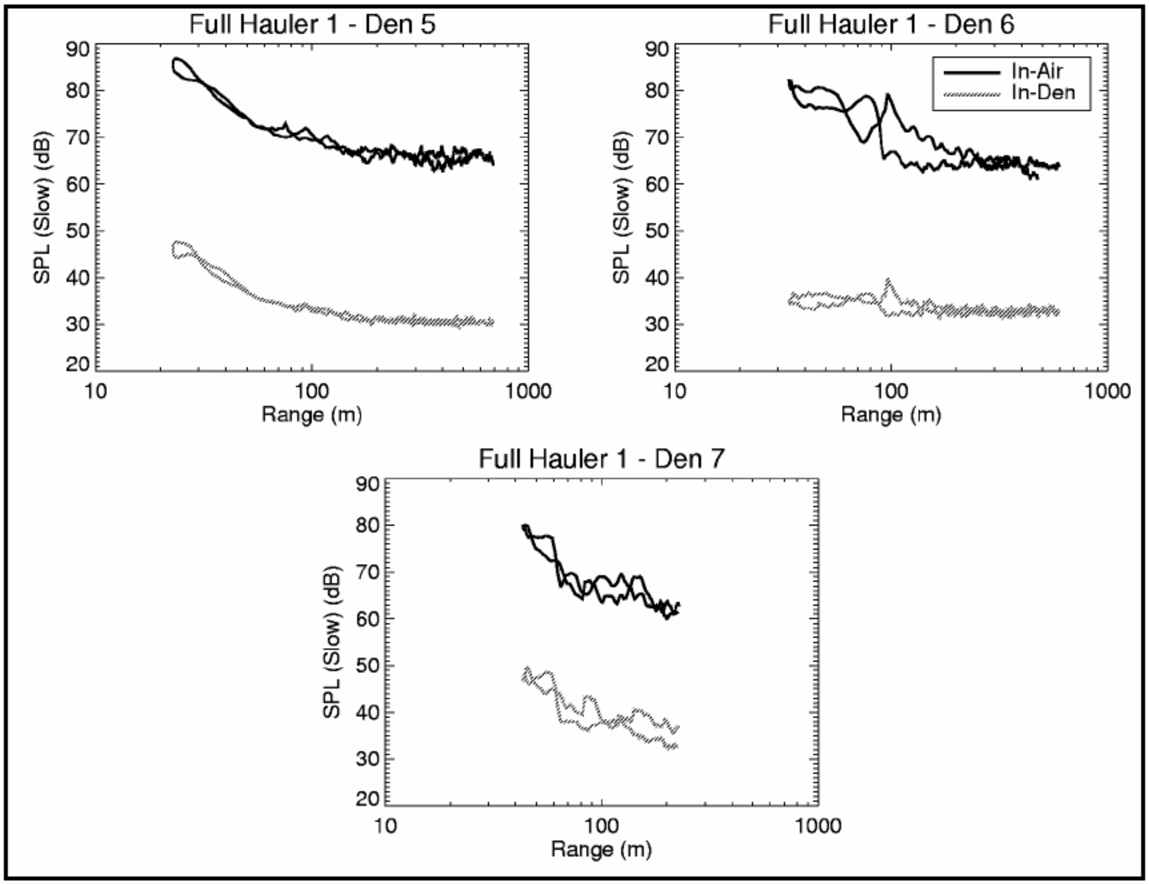

Figure 18: Broadband sound pressure levels (dB re 20 µPa) from a full gravel hauler. Double lines represent approach and passage of the vehicle. Range axes are logarithmic.

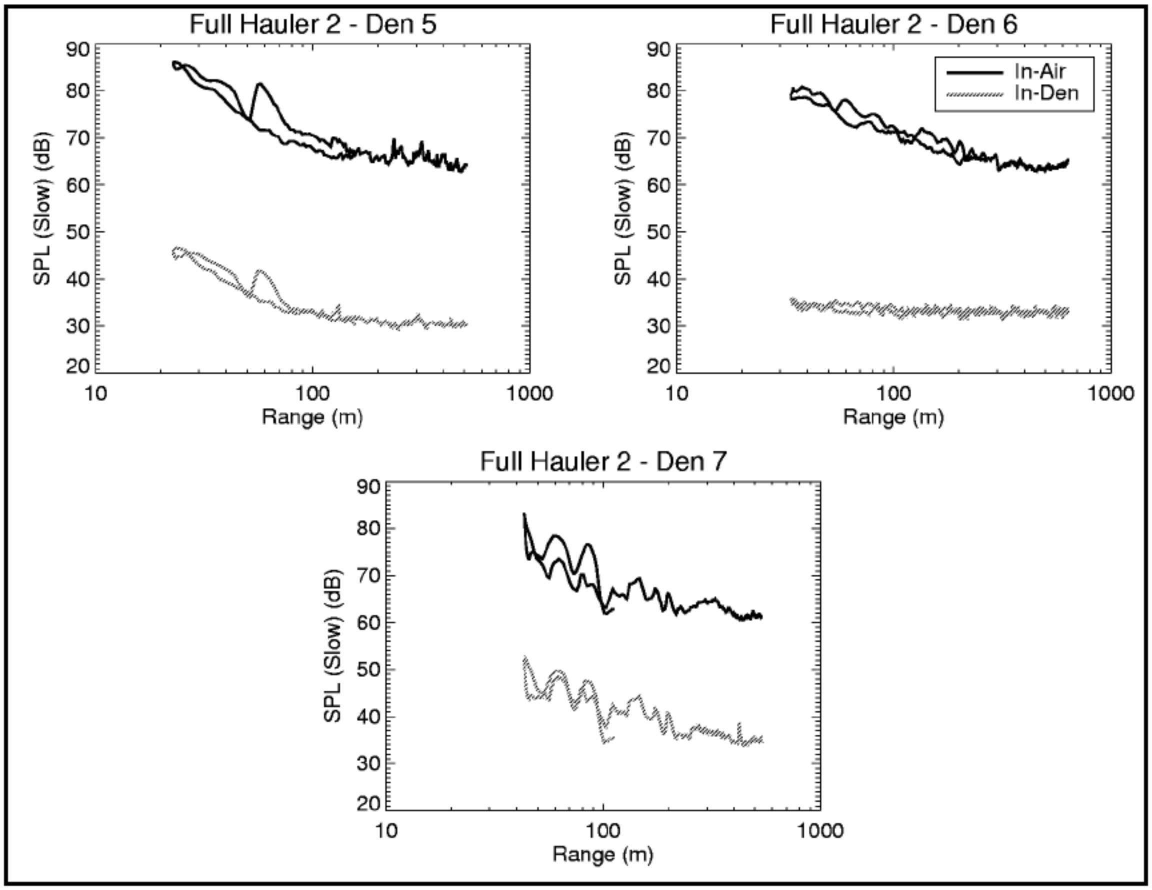

Figure 19: Broadband sound pressure levels (dB re 20 µPa) from a full gravel hauler. Double lines represent approach and passage of the vehicle. Range axes are logarithmic.

Vibration levels from the two individual full gravel haulers, passing the Den 5 site, are shown in figure 20. The approach and pass of the haulers accounts for the double lines in figure 20. Peak acceleration for the full gravel haulers was 3.7 mm/s^2 in the ground and 4.2 mm/s^2 in the snow, each value lower than for the empty gravel haulers. Snow velocity was 2.5 µm/s for the full haulers, and acceleration was < 0.5 mm/s^2 at a range of 60 m (Table 5).

4.1.2.2 Front-End Loader

Noise and vibration measurements of a front-end loader traveling along the Flaxman Island ice road at a speed of 22 kph (14 mph) were made at Den 5 and Den 6. The double lines in figure 21 represent the approach and pass of the front-end loader. The in-air SPL peaked at 81 dB re 20 µPa as the loader passed 12 m from Den 5. The corresponding in-den SPL was 43 dB, a difference of 38 dB (Table 5). The background noise level in the den was 27 dB and noise from the loader reached background levels at a range of 500 m. The spectral distribution of noise from the front-end loader is fairly flat from 10 – 10,000 Hz in air, but in the den, the higher frequencies (> 300 Hz) are reduced by approximately 40 – 50 dB. (Figure 22).

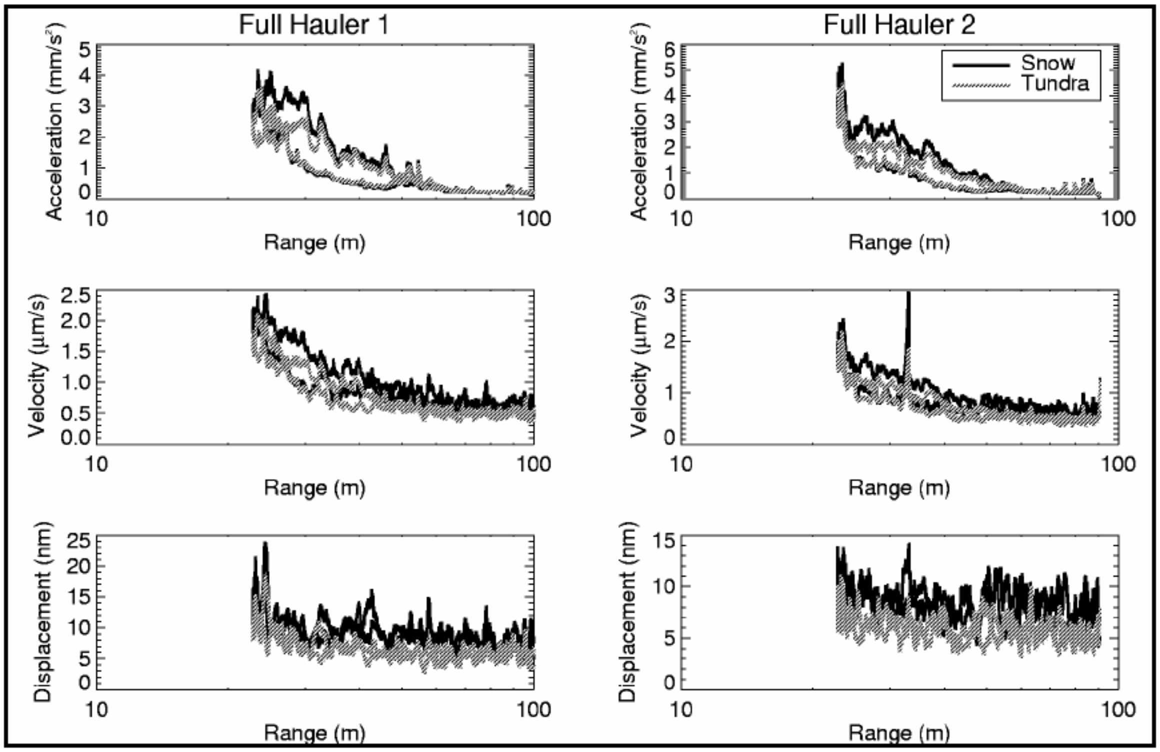

Figure 20: Vibration levels from the passage of two full gravel haulers. Vibration records are from the Den 5 site. Double lines represent approach and passage of the vehicle. (Note: Y-axis scales are different)

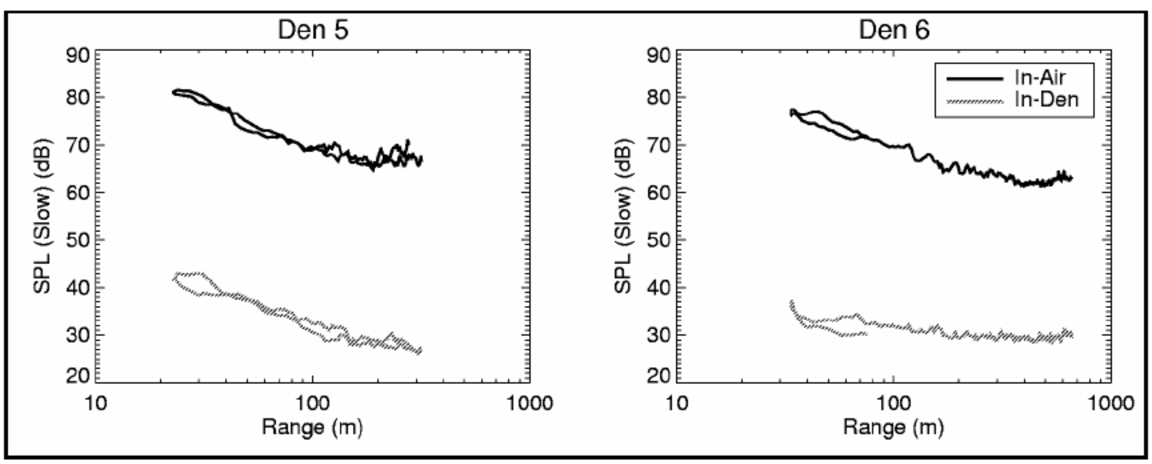

Figure 21: Broadband sound pressure levels (dB re 20 µPa) received from a front-end loader traveling at 22 kph along the ice road. Double lines represent approach and passage of the vehicle. Range axes are logarithmic.

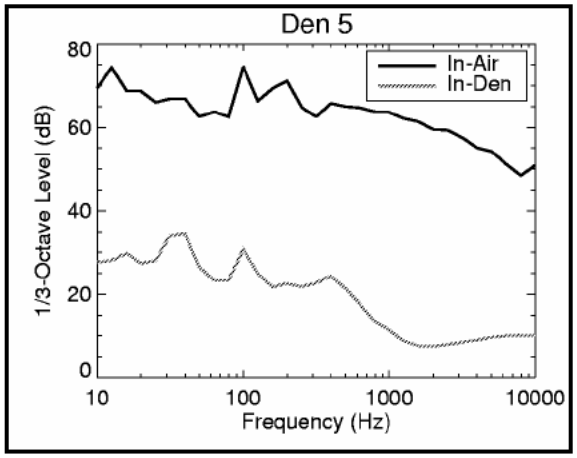

Figure 22: 1/3-Octave band sound pressure levels (re 20 µPa) from a front-end loader measured at a range of 23 meters from Den 5.

Vibration levels from the front-end loader were nearly identical when measured in the snow or in the ground at Den 5 (Figure 23). Peak acceleration in the ground was 8.0 mm/s^2, and was 8.5 mm/s^2 in the snow (Table 6). Acceleration was less than 0.5 mm/s^2 at a range of 60 m from Den 5.

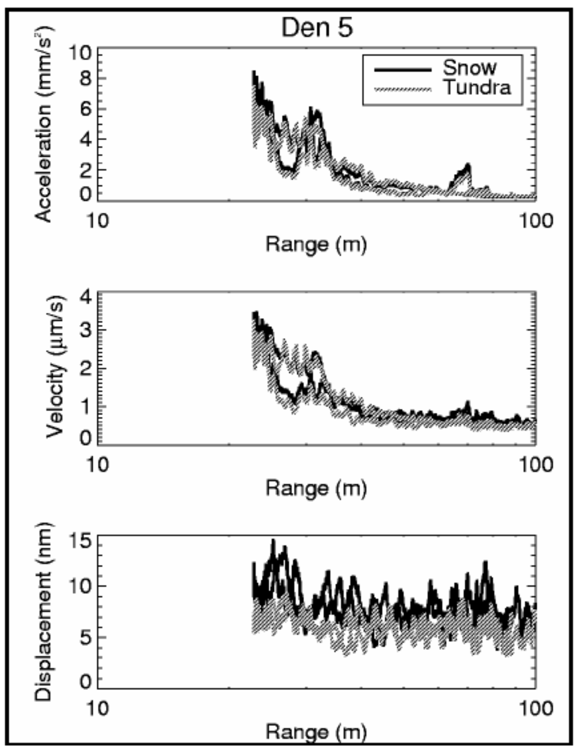

Figure 23: Ground vibration levels from the approach and passage of a front-end loader, measured at Den 5.

4.1.2.3 Pickup Truck

Noise and ground vibration measurements of a standard 1-ton pickup truck traveling along the Flaxman Island ice road at a speed of 32 kph (20 mph) were made at Den 5 and Den 6. Acoustic recordings were only made to a distance of 200 m (Den 5) and 300 m (Den 6; Figure 24). Peak in-air SPL for the pickup truck was 71 dB re 20 µPa at the CPA (12 m). In the den, the peak level was 37 dB re 20 µPa, a difference of 34 dB (Table 5). The pickup truck was indistinguishable from background levels inside the den (25 dB re 20 µPa) at a range of 100 m. The spectral distribution of noise from the pickup truck was dominated by low frequency sounds, but a peak was recorded at about 1000 Hz. All frequencies, especially frequencies above 1000 Hz, were reduced inside the den by 30 – 40 dB (Figure 25).

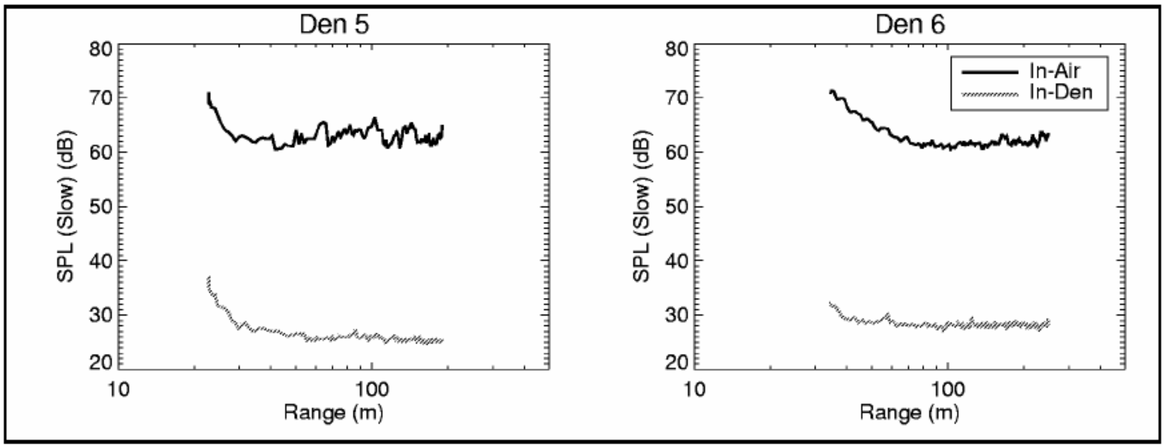

Figure 24: Broadband sound pressure levels (dB re 20 µPa) from a pickup truck.

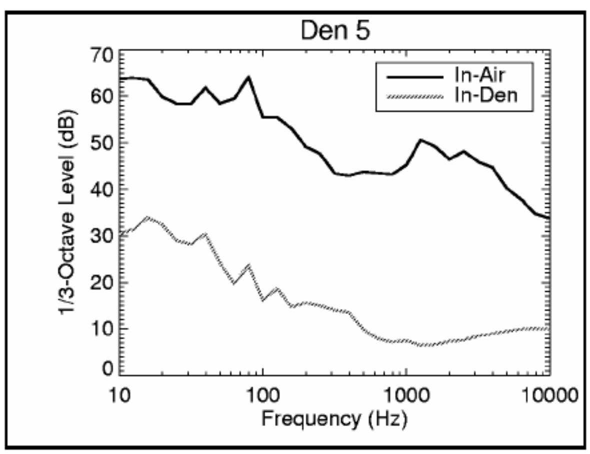

Figure 25: 1/3-Octave band sound pressure levels (dB re 20 µPa) from a pickup truck measured at a range of 23 m from Den 5. Range axis is logarithmic.

Vibration levels measured in the ground and in the snow were nearly identical for the pickup truck at Den 5 (Figure 26). Peak acceleration of 1.5 mm/s^2 in both the ground and the snow was recorded when the pickup truck was at the closest point of approach (22 m). Acceleration was less than 0.5 mm/s^2 when the pickup truck was 43 m from the Den (Table 6).

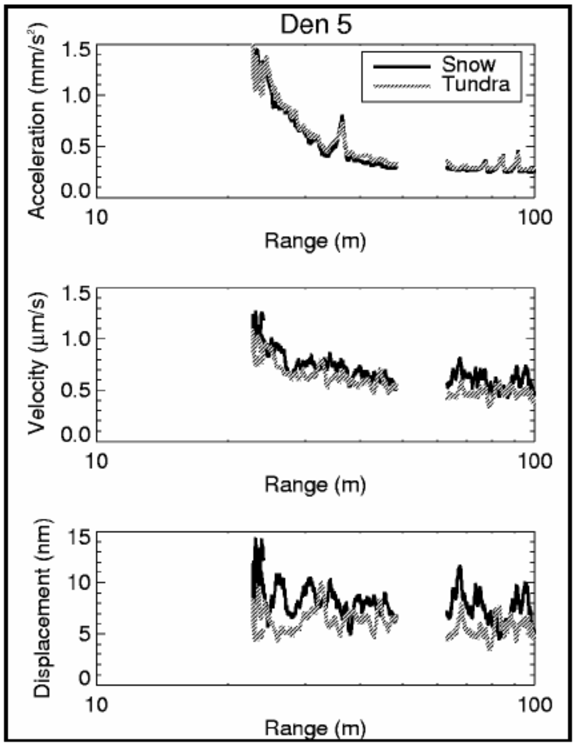

Figure 26: Ground vibration levels from the approach and passage of a pickup truck, measured at Den 5. Missing data between 50-60 m range were contaminated by footstep noise from a person walking near the den.

4.1.2.4 Fuel Truck

Noise measurements of a 4000-gallon Ford L3000 fuel truck traveling along the Flaxman Island ice road at a mean speed of 17 kph (10 mph) were made as the truck approached and passed Dens 5 and 6 (Figures. 27). Vibration measurements were not made. The in-air SPL was 80 dB re 20 µPa at the closest point of approach (12 m), while the in-den SPL was 50 dB, a difference of 30 dB. The ambient background inside the den was 29 dB, and the fuel truck noise was indistinguishable from background levels when the truck was 300 m from the Den (Table 5). Low frequency sounds dominated the fuel truck spectral distribution (Figure 28), and all frequencies were attenuated 35 – 45 dB by the snowpack.

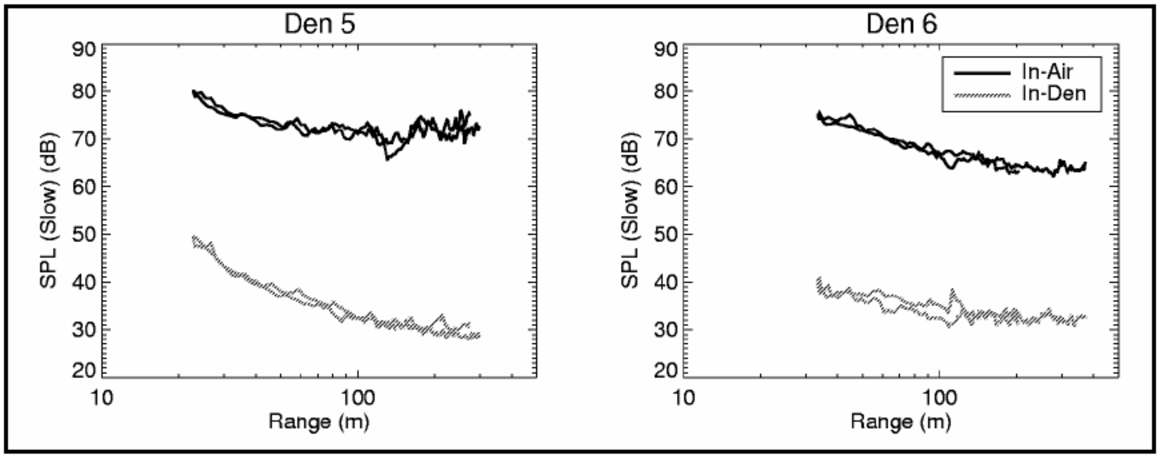

Figure 27: Sound pressure levels (dB re 20 µPa) received from the approach and passage of a fuel truck. Range scales are logarithmic.

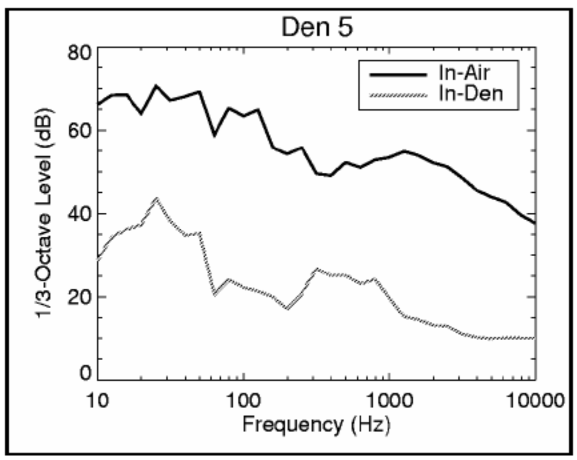

Figure 28: 1/3-Octave band sound pressure levels (dB re 20 µPa) from a fuel truck measured at a range of 23 m from Den 5. Range scales are logarithmic.

4.1.3 Blasting Activities

4.1.3.1 Well Blast Acoustic Data

Maximum sound pressure levels (SPL) in air from the well-casing blast ranged from 116.1 dB re 20 µPa in camp (110 m from the blast site), to 88.6 dB re 20 µPa at Den 7 (1.2 km from the blast site; Table 7). Impulse time weighted sound pressure levels recorded in Dens 5 and 6 (504 and 887 m from the blast) were 101.4 dB and 100.7 dB re 20 µPa, respectively. In the dens, maximum SPL ranged from 76.5 dB re 20 µPa at Den 5 to 72.6 dB in Den 6. Interestingly, SPL in Den 6 was lower than in Den 7 (74.4 dB), although Den 7 was 396 m farther from the blast. Peak pressure (measured as the highest single recorded value with no time integration) ranged from 125.7 dB re 20 µPa in air at the camp to 97.1 dB at Den 7. Peak pressure in dens ranged from 80.8 dB in Den 5 to 77.1 dB in Den 6. Peak pressure in Den 7 was again higher than in Den 6, despite the increased distance from the blast. This may be a function of the thicker ceiling in Den 6 than in Den 7.

Table 7: Maximum sound pressure levels (SPL; re 20 µPa) and peak pressure levels from the 8.7 kg blast.

	Range (m)	Max SPL (dB)		Peak Pressure (dB)	
Recording Site	from blast	In-Air	In-Den	In-Air	In-Den
Camp	110	116.1	–	125.7	–
Den 5	504	101.4	76.5	108.9	80.8
Den 6	887	100.7	72.6	108.7	77.1
Den 7	1283	88.6	74.4	97.12	78.9

The blast, recorded 110 meters from the well site, is characterized by rapid changes in pressure that equilibrate within 0.2 sec. (Figure 29). The spectral distribution of the blast shows that the majority of acoustic energy was concentrated at frequencies < 30 Hz. (Figure 29). Because of continuous high wind conditions, low-frequency ambient noise levels were already high at the time of this recording. The blast was undetectable by the in-air recorders over wind noise at the more distant recording sites. Inside the dens, however, noise from the blast was well above the ambient level even at the maximum recording range of 1.2 km (Table 7, Figure 30).

A small pulse appeared two seconds before the arrival of the main acoustic pulse in Den 5 (Figure 30). This pulse corresponds to the arrival of the ground wave from the blast, and may be due to the microphone detecting ground vibrations conducted through the microphone stand. The ground wave was not detected by the more distant microphones in Dens 6 or 7.

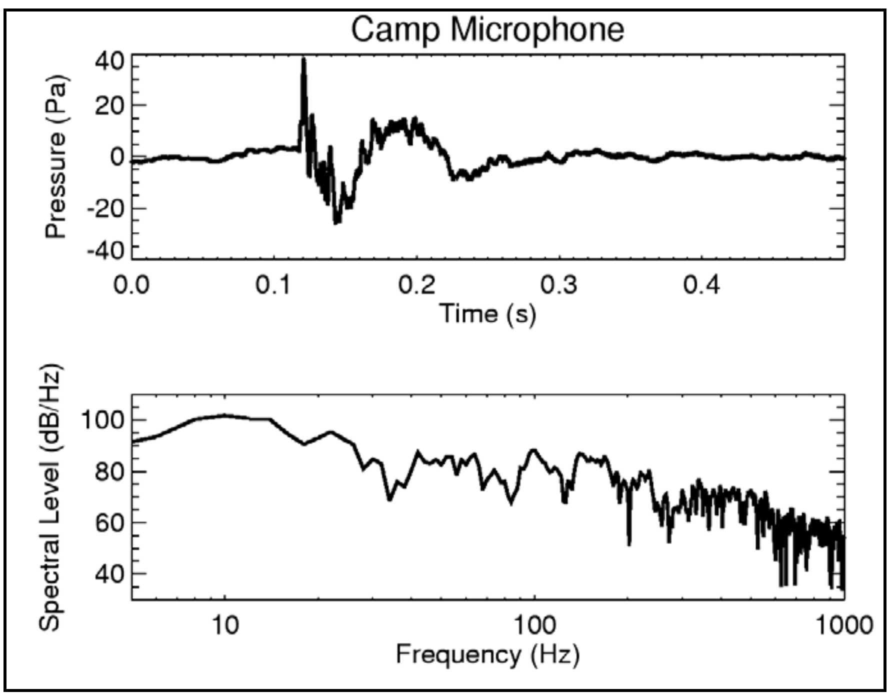

Figure 29: Audio waveform and spectrum of the sound impulse from the 8.7 kg blast. The camp microphone recorded acoustic data, 110 meters from the blast location. Frequency axis is logarithmic.

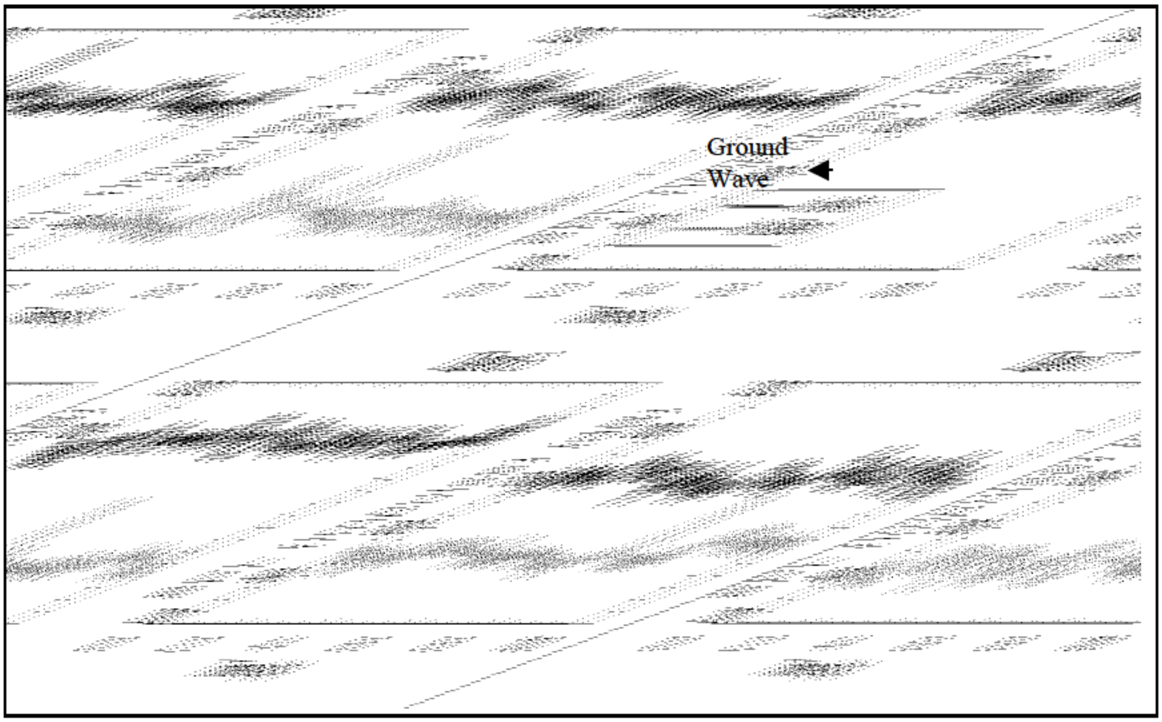

Figure 30: Broadband sound pressure levels (dB re 20 µPa) for the 8.7 kg blast. Sound level computations were performed using impulse (32 ms) time weighting and flat frequency weighting. Note the ground wave pulse in den 5.

4.1.3.2 Well Blast Vibration Data

For the well-casing blast, ground acceleration was directly measured by tri-axial accelerometers at each of the artificial dens. Ground velocity and displacement were obtained through integration of the accelerometer data. For the blast event, all of the measured ground vibration axes (L, T and Z), as well as their vector sum, are shown for Dens 5, 6 and 7 (Figures 31-38). Data from all dens clearly show the separate arrivals of two distinct seismic phases. The first arrival undoubtedly corresponds to compressional (P) waves resulting from the blast event. P-waves travel faster than all other seismic phases and contain higher frequency vibrations. The second arrival most likely corresponds to shear (S) waves and Rayleigh waves, which are lower frequency, slower traveling seismic phases.

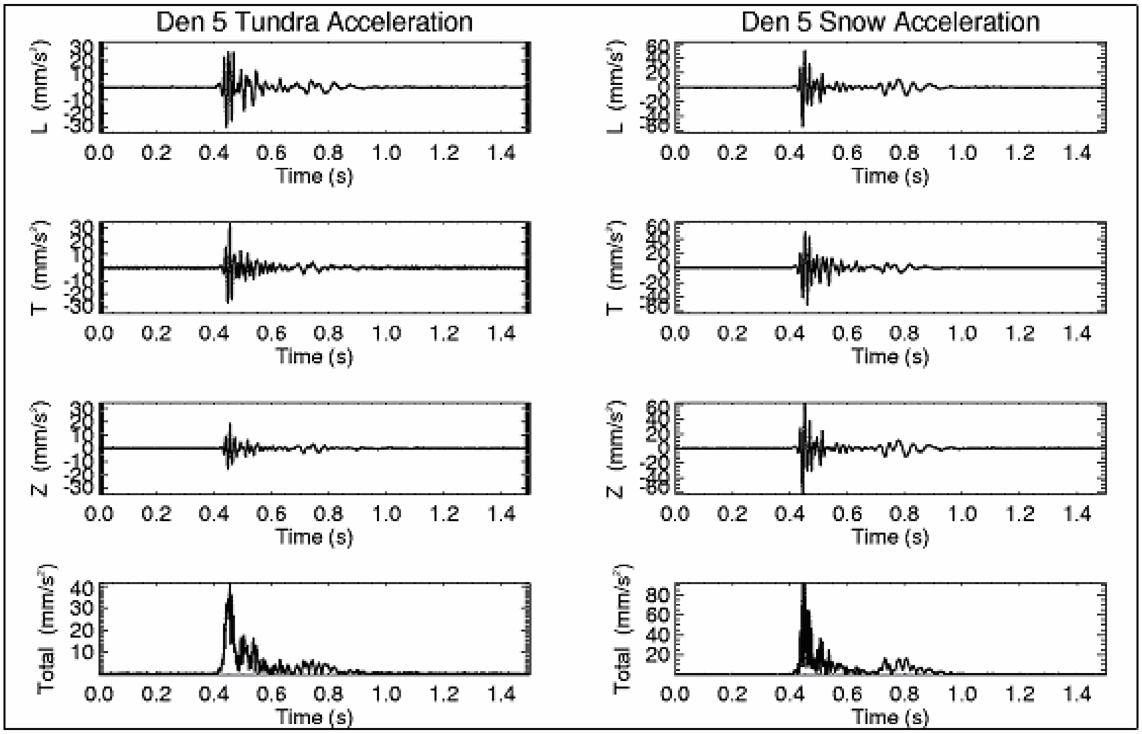

Figure 31: Den 5 ground acceleration due to blast at well 500 m away. Note different y-axis scales.

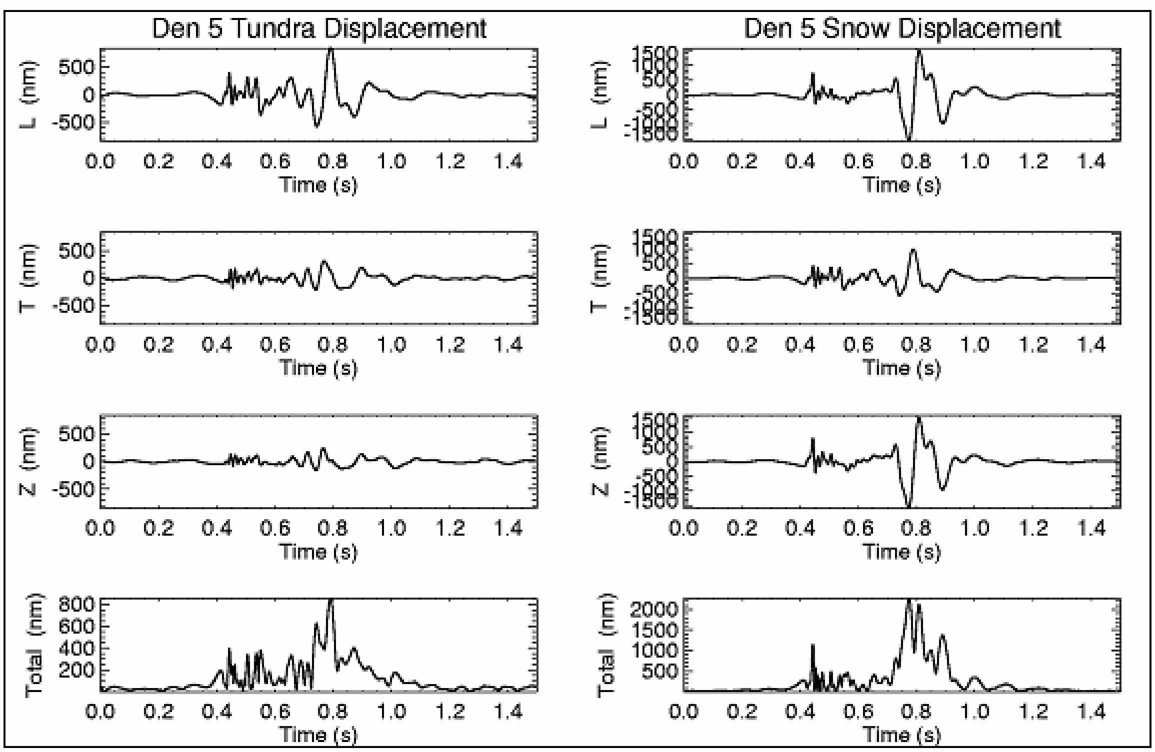

Figure 32: Den 5 ground displacement due to blast at well 500 m away. Note different y-axis scales.

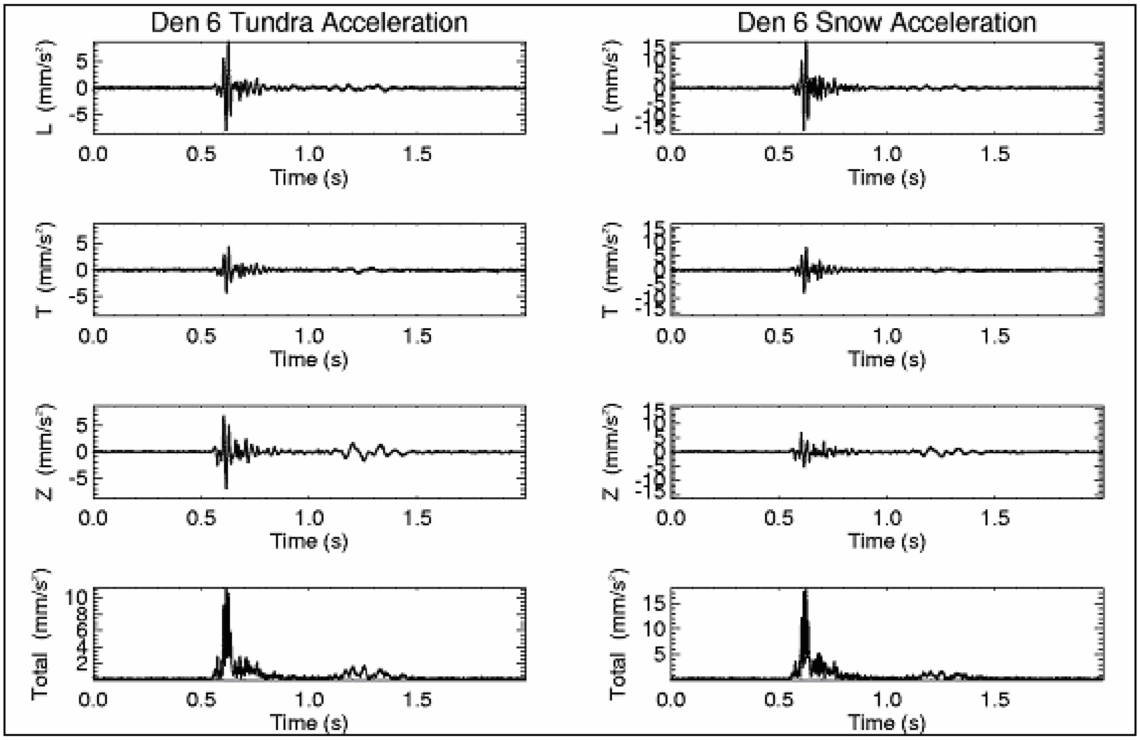

Figure 33: Den 6 ground acceleration due to blast at well 890 m away. Note different y-axis scales.

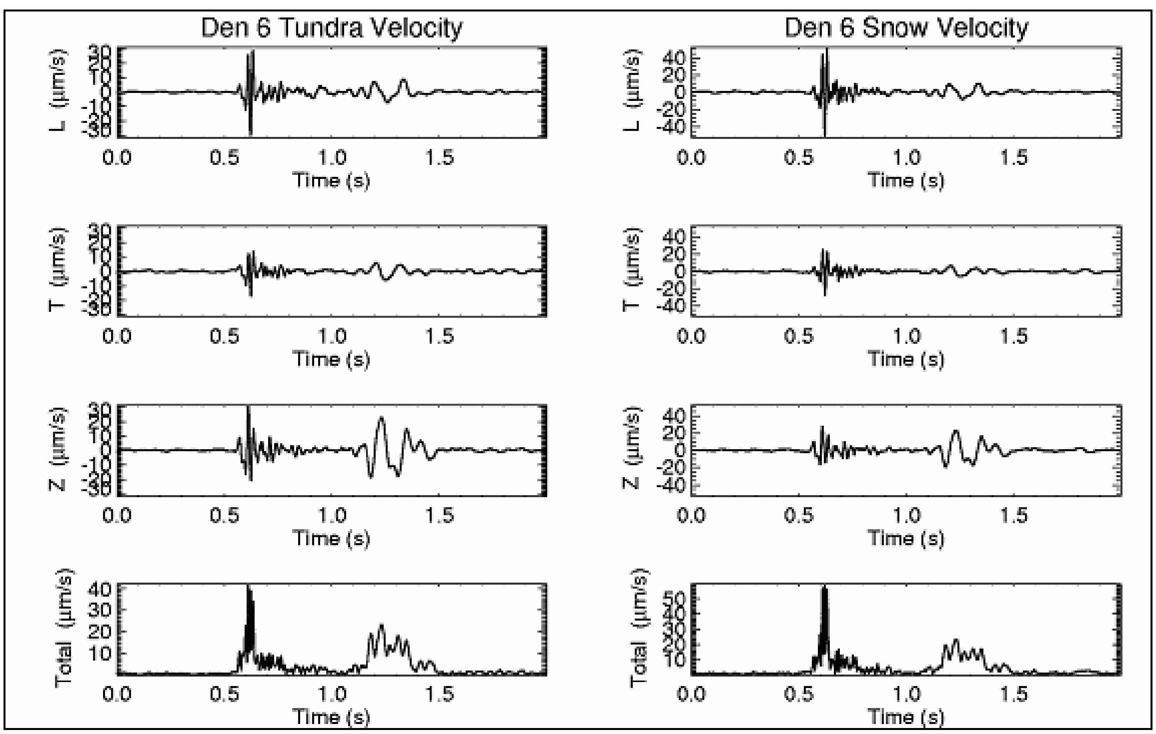

Figure 34: Den 6 ground velocity due to blast at well 890 m away. Note different y-axis scales.

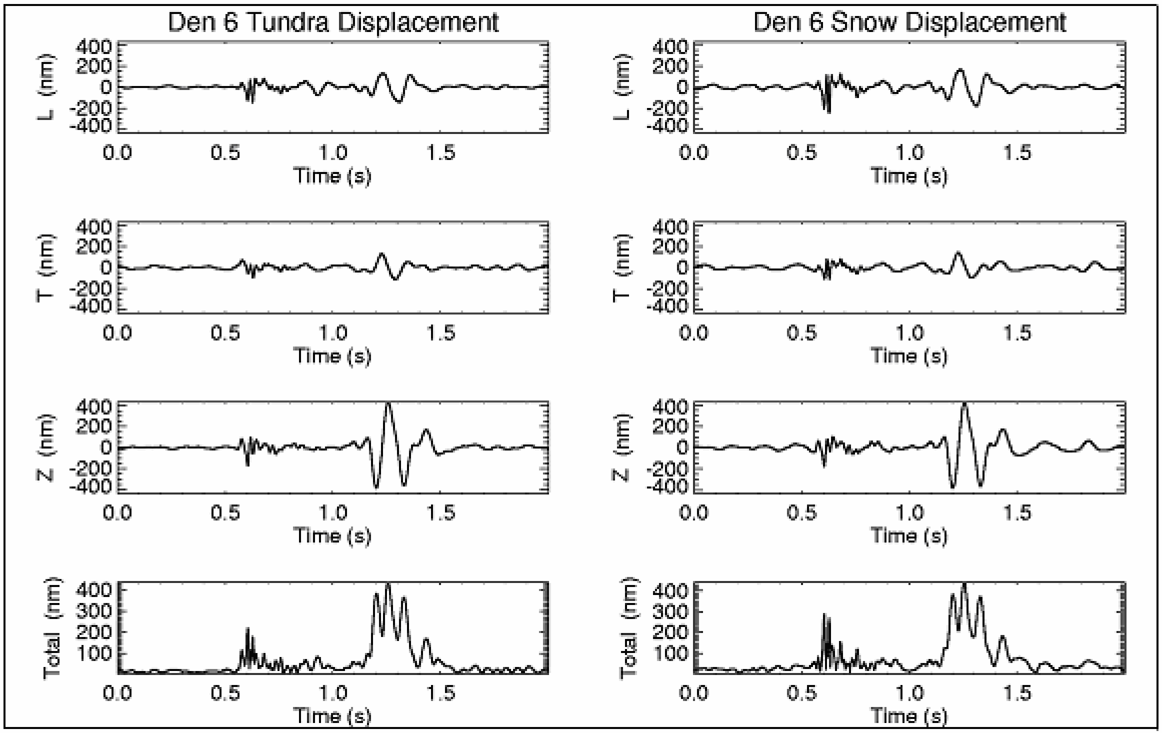

Figure 35: Den 6 ground displacement due to blast at well 890 m away.

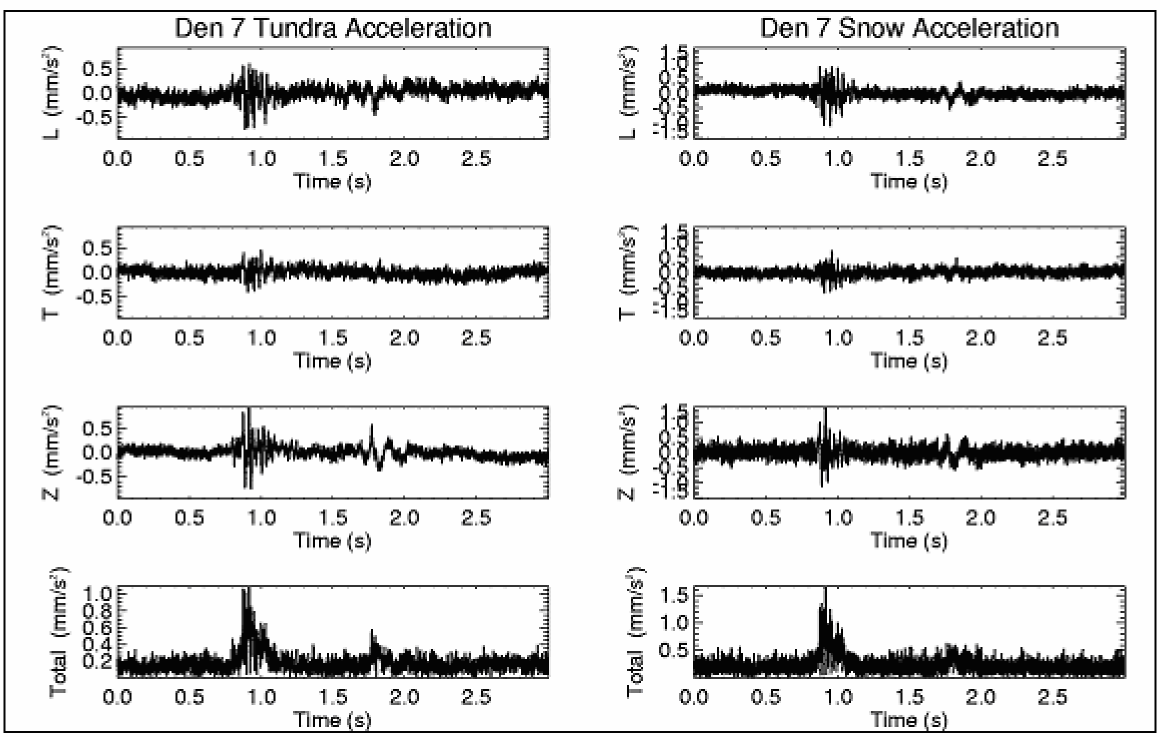

Figure 36: Den 7 ground acceleration due to blast at well 1280 m away. Note different y-axis scales.

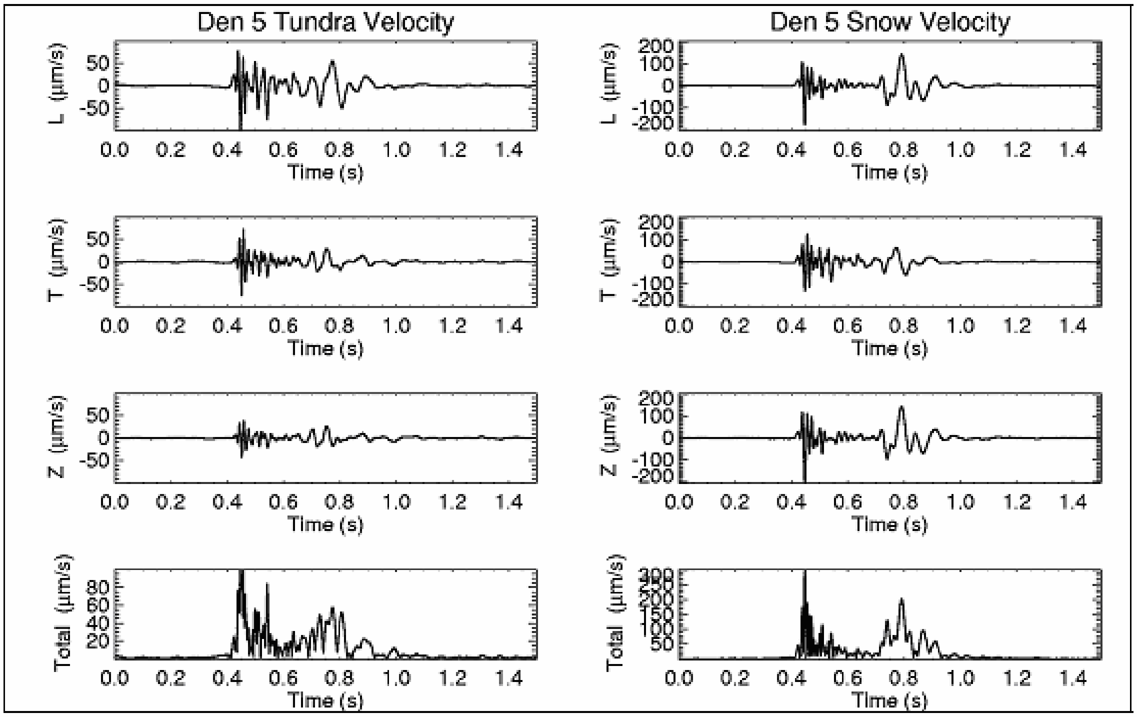

Figure 37: Den 5 ground velocity due to blast at well 500 m away. Note different y-axis scales.

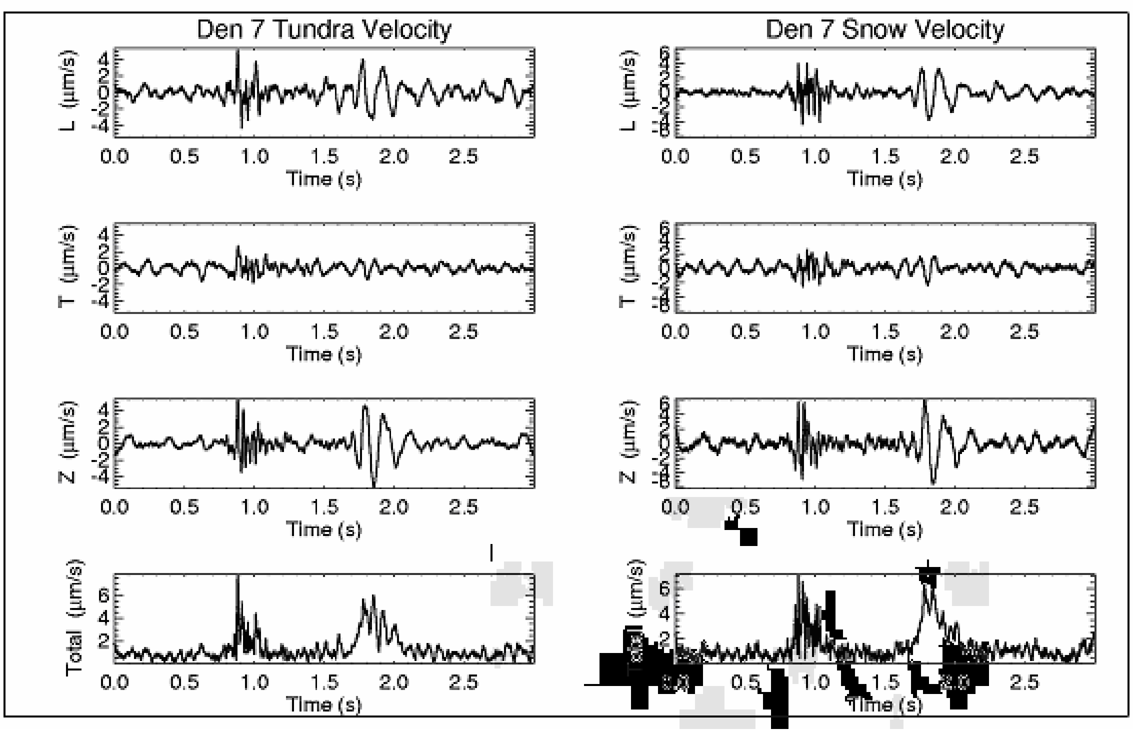

Figure 38: Den 7 ground velocity due to due to blast at well 1280 m away. Note different y-axis scales.

Peak vibration measurements (Table 8) show clear attenuation of vibration with distance from the blast site. Peak acceleration in tundra was nearly 40 times greater at Den 5 (504 m from the blast site) than at Den 7 (1,283 m from the blast site) and acceleration in snow was about 54 times greater at Den 5 than Den 7. Similarly, peak velocity was 12 times greater in tundra and 42 times greater in snow at Den 5 than Den 7, and peak displacement was 7 times greater in tundra and 17 times greater in snow at Den 5 than Den 7. Den 6 (887 m from the blast site) was intermediate in all vibration measurements, in contrast to the sound measurements reported above. Note that no absolute time reference was available and so the vibration data are not presented relative to the blast time.

Table 8: Peak measured blast vibration levels, acceleration, velocity, and displacement in-tundra and in-snow for Dens 5, 6 and 7.

		Peak Acceleration (mm/s^2)		Peak Velocity (μm/s)		Peak Displacement (nanometers)	
Site	Range (m)	Tundra	Snow	Tundra	Snow	Tundra	Snow
Den 5	504	41.3	91.9	99.7	301	855	2260
Den 6	887	11.2	18.0	41.9	59.7	435	441
Den 7	1283	1.1	1.7	7.8	7.1	119	127

Spectrograms of the vertical ground acceleration (both in-tundra and in-snow), as measured at Den 6, (Figure 39 and 40, respectively) show that the ground vibration due to the blast event occurred primarily at frequencies between 10 Hz and 150 Hz. Additionally, the dominant frequency of the initial P-wave arrival (60 Hz) is clearly greater than the dominant frequency of the secondary arrival (25 Hz).

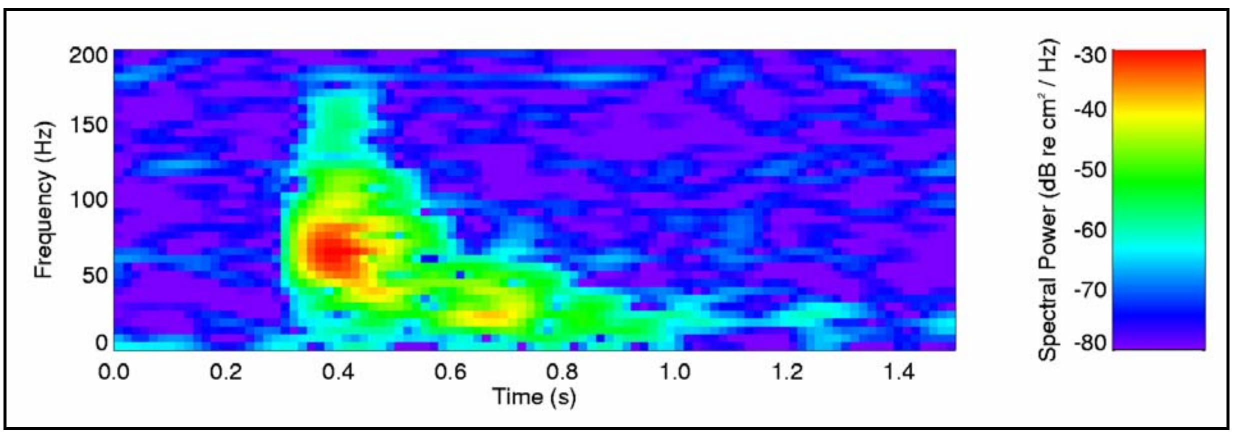

Figure 39: Spectrogram of the tundra vibration (Z acceleration) due to the blast, as measured at Den 6.

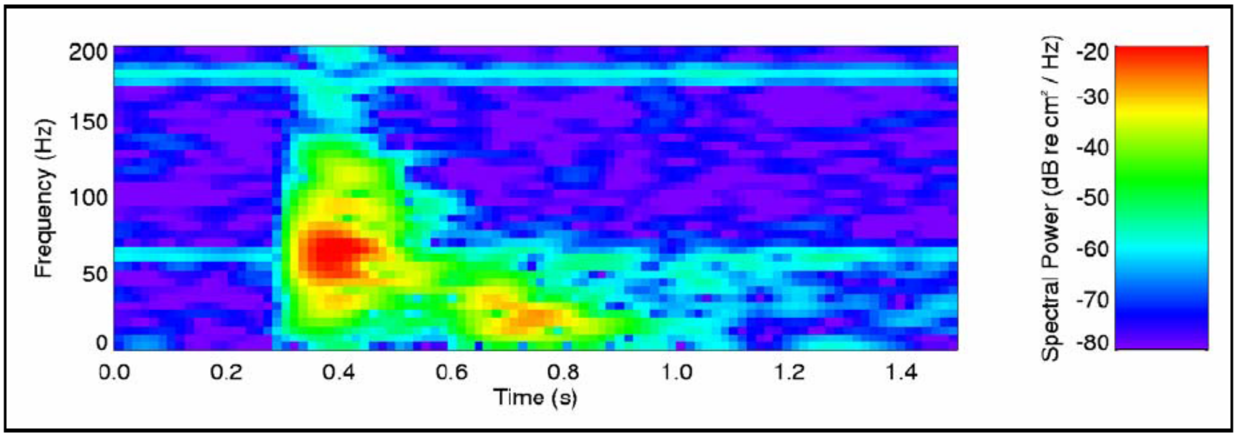

Figure 40: Spectrogram of the snow vibration (Z acceleration) due to the blast, as measured at Den 6.

4.1.4 Experimental Trials

4.1.4.1 Tracked Vehicles

Acoustic and physical vibration recordings of the Hägglunds tracked vehicle were made as it traversed the tundra past the monitoring sites at Den 5 and Den 7. The mean wind speed and direction at the time of recording was 13 kph from 180°. The closest point of approach was 18 m near Den 5. At 18 m, the SPL in air was 85 dB, and was 55 dB in the den (Figure 41), an attenuation of 30 dB through the snow (Table 5). The spectral distribution of the noise from the Hägglunds was dominated by low frequencies, especially below 100 Hz (Figure 42). Inside the den, the SPL decreased quickly at frequencies above 100 Hz.

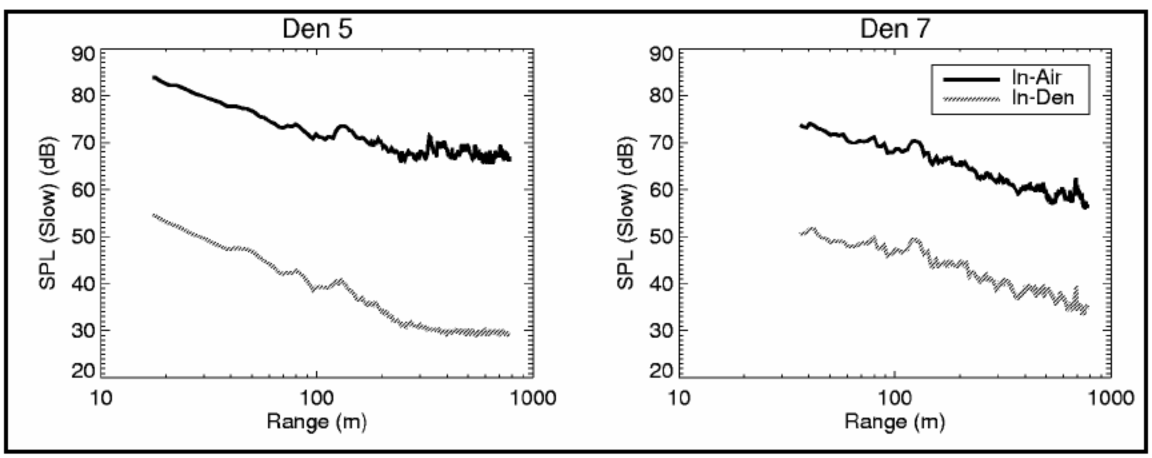

Figure 41: Sound pressure levels (dB re 20 μPa) from the Hägglunds BV206 versus range. Range axes are logarithmic.

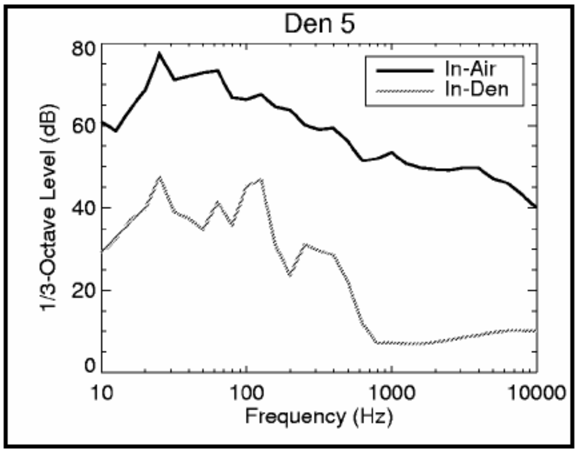

Figure 42: 1/3-octave band sound pressure levels (dB re 20 μPa) from the Hägglunds BV206 measured at a range of 17 meters from Den 5.

Ground vibration data were collected as the vehicle moved toward, then away from the recording site, accounting for the double lines in figure 43. Axial measurements (T, L, and Z) were consistent in all measurements, so only the total integration of the acceleration, velocity, and displacement are shown. In Den 5, acceleration measured in the tundra and snow were similar at CPA, 10 mm/s^2 in tundra and 11 mm/s^2 in snow. For the remaining measurements in Den 5, and for all measurements in Den 7, values were higher in snow than in the tundra. Acceleration was < 0.5 mm/s^2 when the vehicle was 90 m away (Table 6).

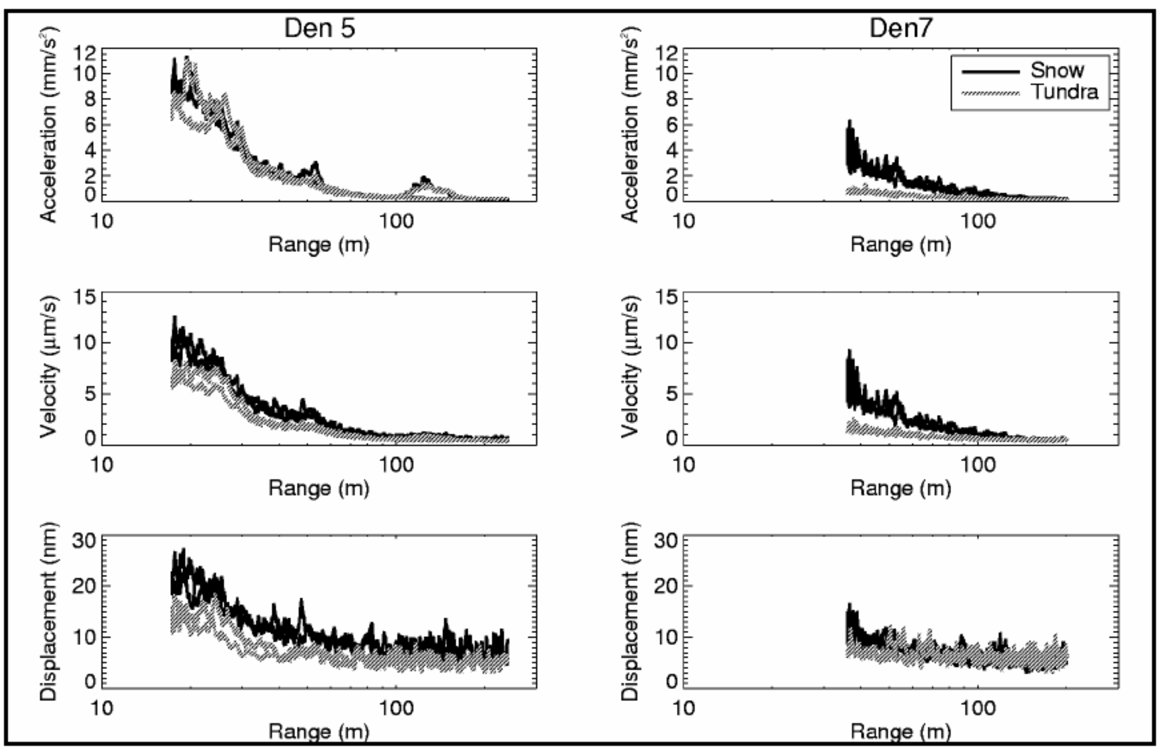

Figure 43: Ground vibration levels received from the Hägglunds BV206, versus range. Range axes are logarithmic. Double lines represent the approach and departure of the Hägglunds past each den along the oval path in Figure 14.

Acoustic and vibration data were obtained for a Tucker Sno-Cat as it followed a path similar to the Hägglunds', at a mean speed of 18 kph. The mean wind speed and direction at the time of recording was 11 kph from 180°. The CPA for the Tucker was 20 m from Den 5. At 20 m, the in-air SPL was 80 dB re 20 µPa, and inside the den SPL was 38 dB, an attenuation of 42 dB (Table 5, Figure 44). The background SPL in the den was 27 dB, 11 dB below the Tucker noise (Table 5). The Tucker was undetectable above background levels when the vehicle was 400 m from the den. The noise from the Tucker was dominated by low frequencies (Figure 45), with a small contribution at frequencies between 400 and 1100 Hz. The higher frequencies were almost completely attenuated by the snow.

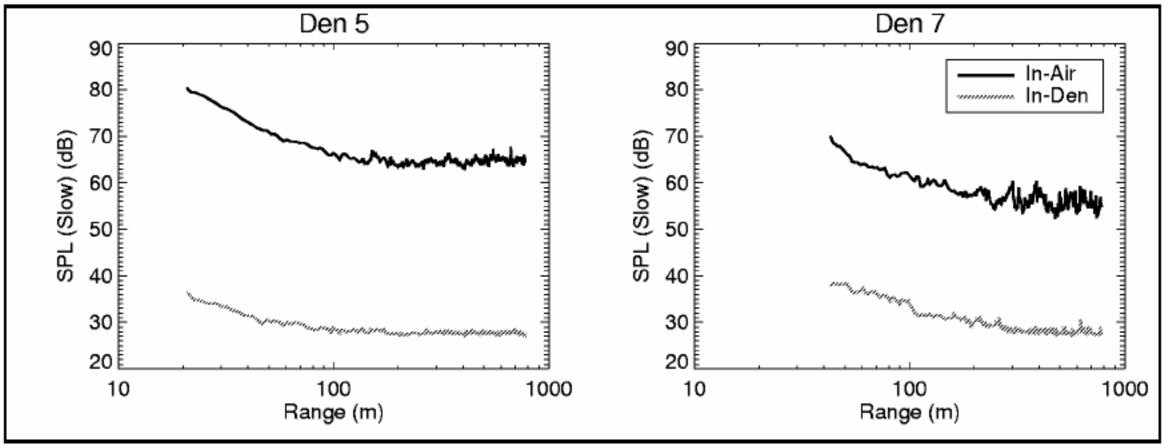

Figure 44: Sound pressure levels (re 20 µPa) from the Tucker Sno-Cat versus range. Range axes are logarithmic.

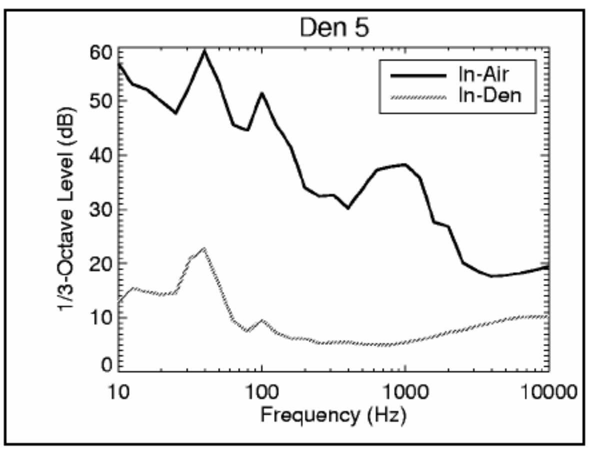

Figure 45: 1/3-Octave band sound pressure levels (re 20 µPa) from the Tucker Sno-Cat measured at a range of 21 meters from Den 5.

Ground vibration levels were much lower for the Tucker than the Hägglunds, ground and snow acceleration were 1.2 and 1.5 mm/s^2, respectively (Table 6). All ground vibrations dropped to near zero very quickly and acceleration dropped to < 0.5 mm/s^2 within 30 m (Table 6, Figure 46).

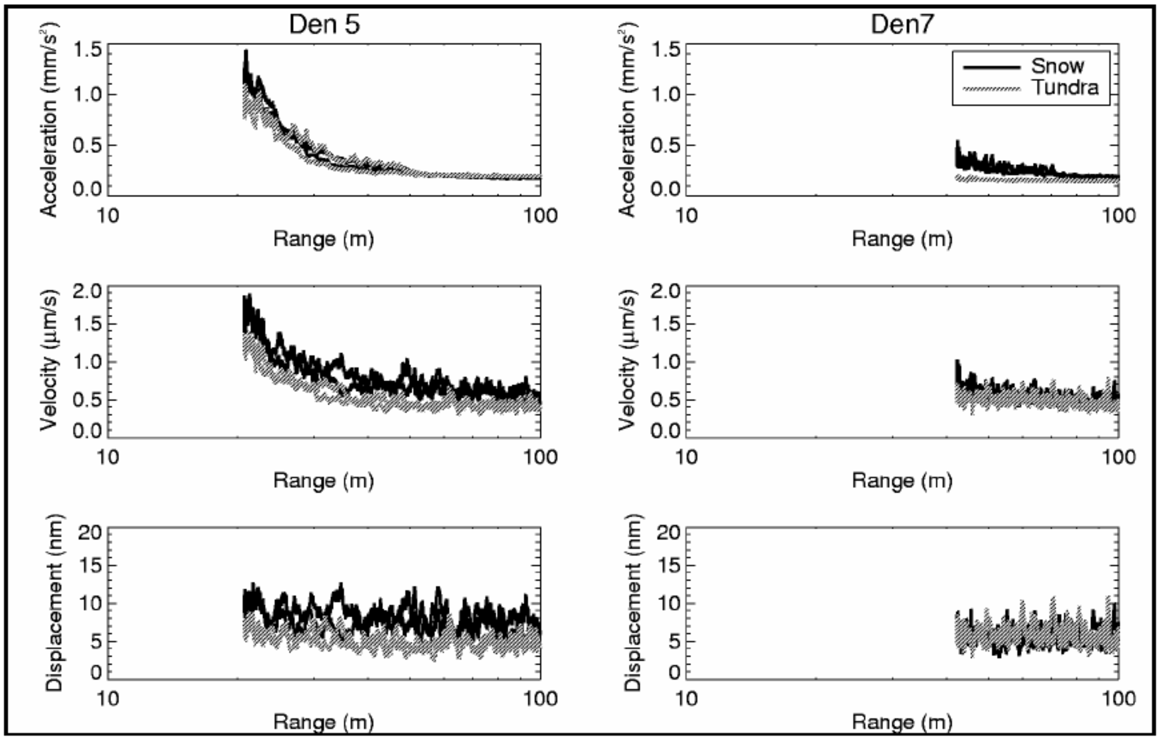

Figure 46: Ground vibration levels received from the Tucker Sno-Cat, versus range. Range axes are logarithmic. Double lines represent approach and departure of the vehicle.

4.1.4.2 Helicopter Overflights

Acoustic and vibration recordings were made of Bell 206 Jet Ranger, and Bell 212 helicopters from all den sites. Fly-by data are presented for dens 5, 7, and 8; other maneuvers were performed only near den 6. The acoustic recording system at den 6 malfunctioned during a significant portion of the Bell 212 recording period. It was fully operational for the Bell 206 recordings. Recordings made at all other den sites for both helicopters were satisfactory for analyses. The data related to take-offs and landings for the Bell 212 helicopter are limited as a result of the den 6 recorder failure. Consequently, only the fly-by data at different altitudes are presented for the Bell 212. A more comprehensive set of measurements is presented for the Bell 206. The wind speed at the time of recording was 32 kph (20 mph) from 180°.

The in-air spectral distribution for the Bell 206 was dominated by low- and mid-frequencies with peak pressure levels near 110 dB (Figure 47). The in-den spectral distribution was dominated by low frequencies, with the mid- and high-frequency noise attenuated strongly by the snow (approximately 60 dB at 10,000 Hz). Peak pressure levels for the in-den measurements were approximately 80 dB around 10 Hz. The in-air spectral distribution from the Bell 212 was dominated by low-frequency sounds, in Den 8, the low-frequency sounds dominated, with a strong attenuation of sounds above 100 Hz.

The Bell 206 was the loudest continuous noise source measured in the study. Broadband, unweighted sound pressure levels in air ranged from 113 dB re 20 μPa when the helicopter was landing 10 m from Den 6 to 91 dB re 20 μPa while the helicopter was hovering 130 m above the den (Table 9). Within Den 6, SPL ranged from 82 dB re 20 μPa for the helicopter hovering 16 m above the Den to 58 dB for the helicopter hovering 130 m above the den. The snow above Den 6 reduced helicopter sound pressure levels by approximately 30 dB for all helicopter activities.

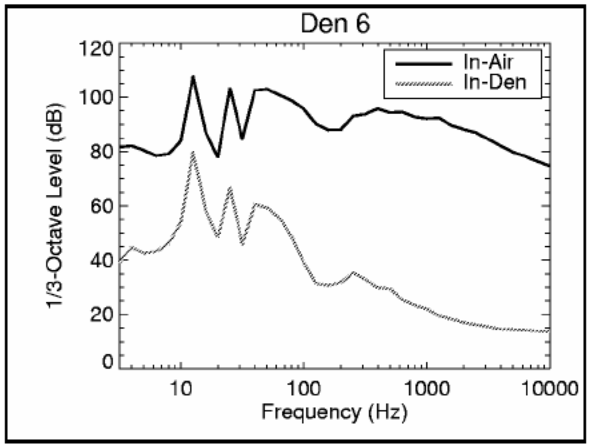

Figure 47: 1/3-Octave band levels (dB re 20 µPa) from the Bell 206 landing 10 m from Den 6. Frequency axis is logarithmic.

In-air and in-den SPL from the Bell 206 do not appear to be strongly related to elevation or distance from the recorder (Figures 48 - 52), although in most cases pressure levels dropped as the range increased. In some cases, the in-air and in-den pressure levels remained nearly constant as the helicopter moved away (e.g. Figure 48, Den 7), or showed small increases (e.g. Figure 50, Den 7). Helicopter maneuvers were not recorded in sufficient detail to correlate SPL with these maneuvers, but pressure is probably influenced by rotor angle and other factors that change as the maneuvers change.

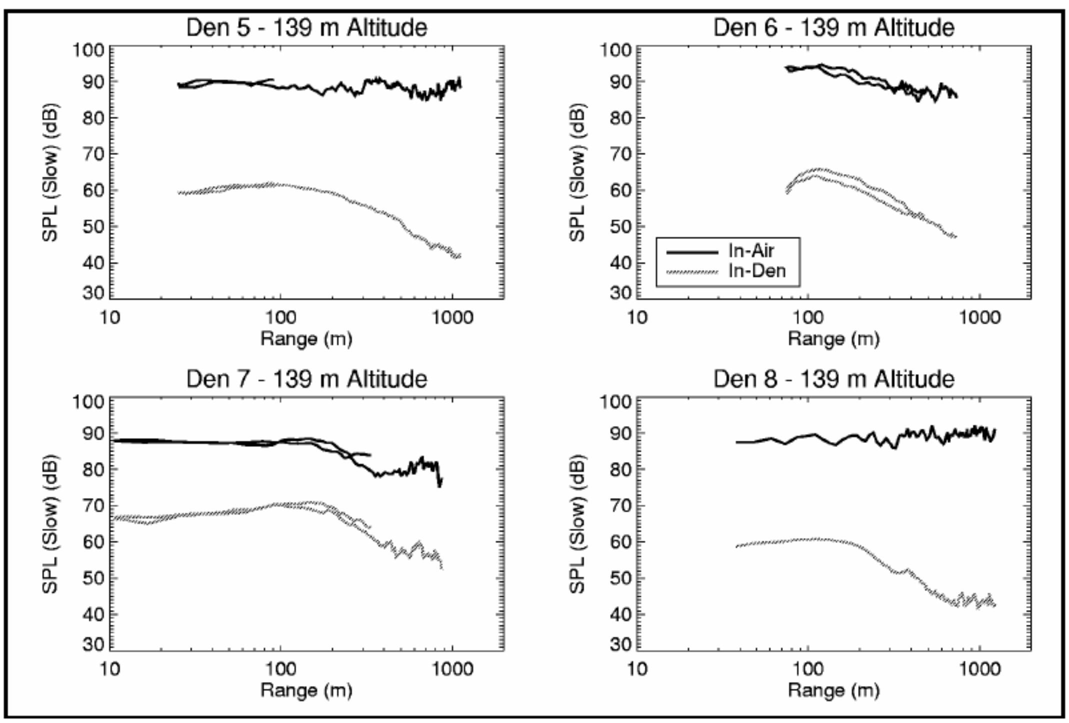

Figure 48: Sound pressure levels (dB re 20 µPa) from Bell 206 flying at 139 m altitude with mean airspeed 43 kph. Range axes are logarithmic.

Table 9: Broadband, unweighted received sound levels, measured at Den 6, for the Bell 206 performing a selection of common helicopter activities. Uncertainties are standard deviations.

	Sound Level (slow-flat) (dB re 20 µPa)	
206 Helicopter Activity	In-Air	In-Den
Landing 10 m away	113.3 ± 0.3	80.6 ± 0.5
Hovering 16 m above den	110.0 ± 0.3	82.2 ± 0.5
Hovering 30 m above den	105.9 ± 0.7	76.4 ± 0.5
Hovering 60 m above den	98.6 ± 0.3	67.7 ± 0.7
Hovering 130 m above den	91.0 ± 0.4	58.3 ± 0.6
Circling 60 m away, 100 m altitude	92.5 ± 1.3	62.7 ± 1.5

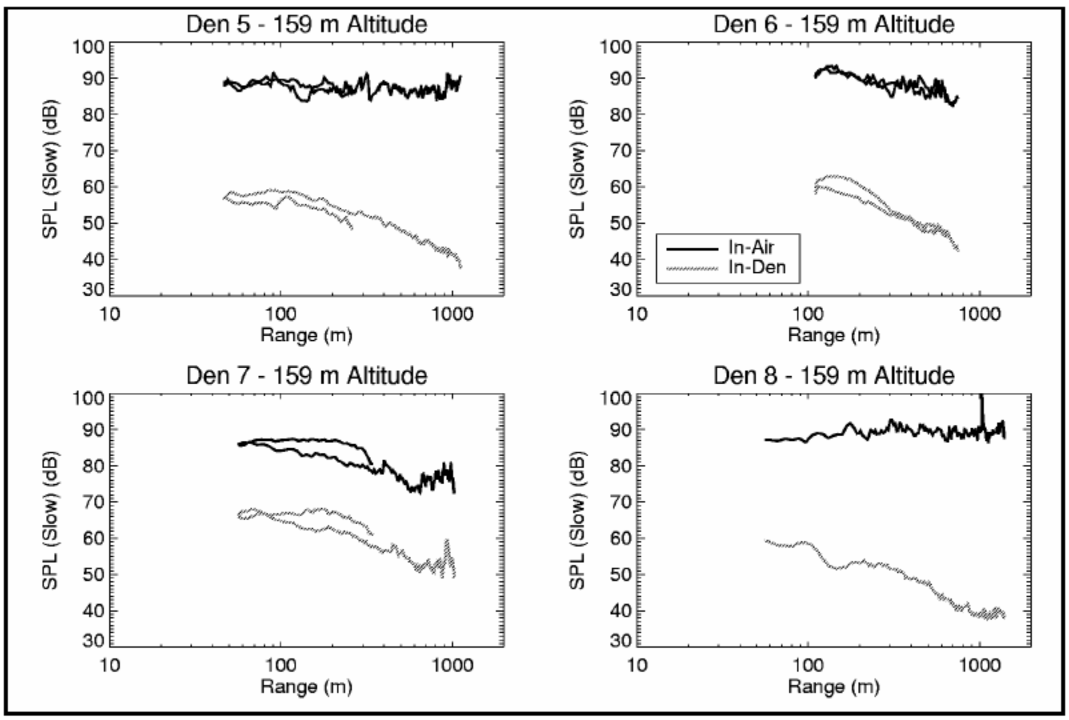

Figure 49: Sound pressure levels (dB re 20 µPa) from Bell 206 flying at 159 m altitude with mean airspeed 32 kph. Range axes are logarithmic.

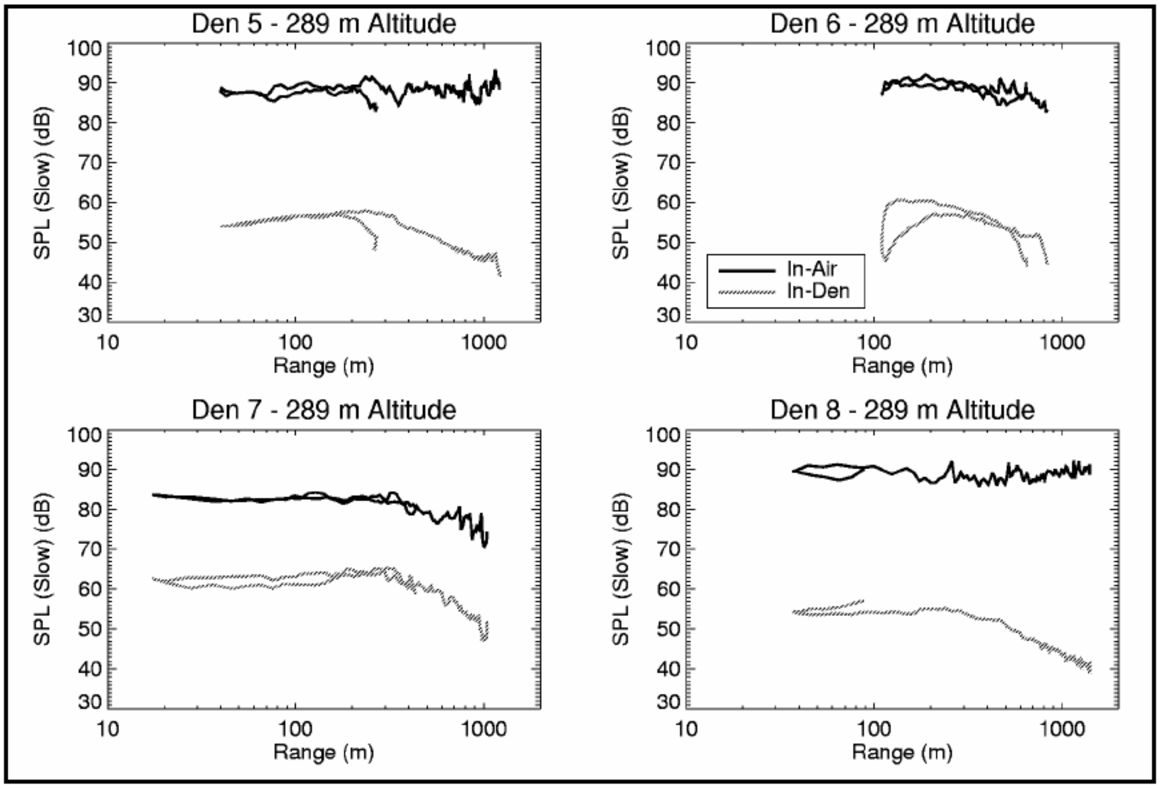

Figure 50: Sound pressure levels (dB re 20 µPa) from Bell 206 flying at 289 m altitude with mean airspeed 45 kph. Range axes are logarithmic.

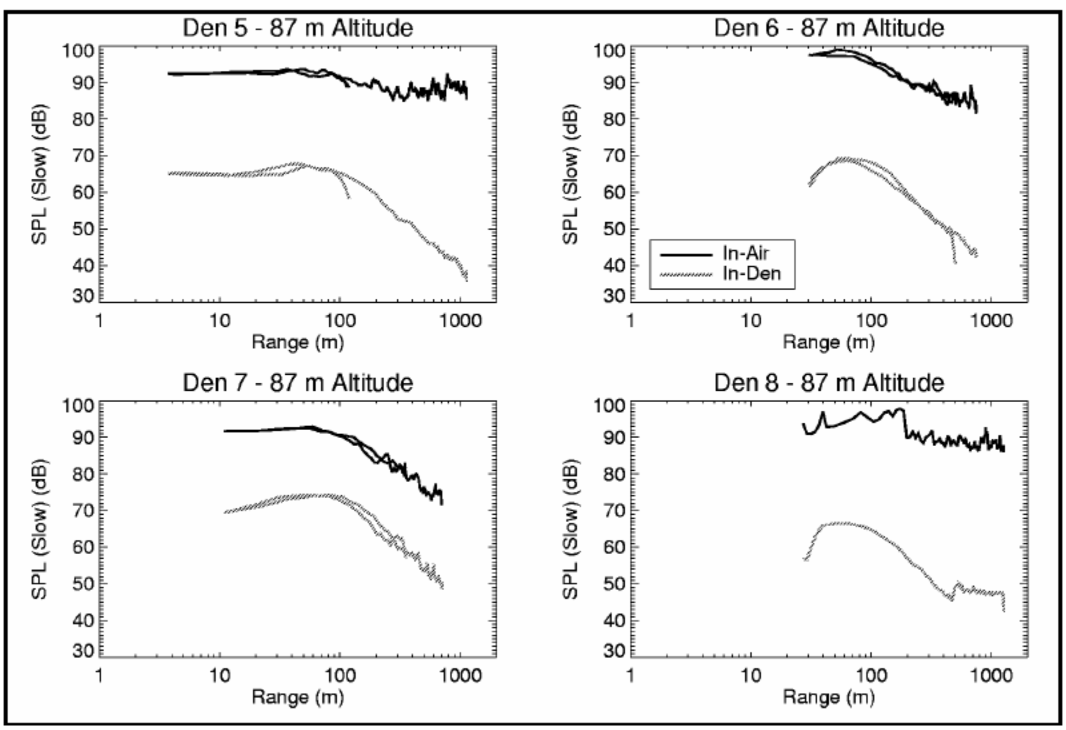

Figure 51: Sound pressure levels (dB re 20 µPa) from Bell 206 flying at 87 m altitude with mean airspeed 33 kph. Range axes are logarithmic.

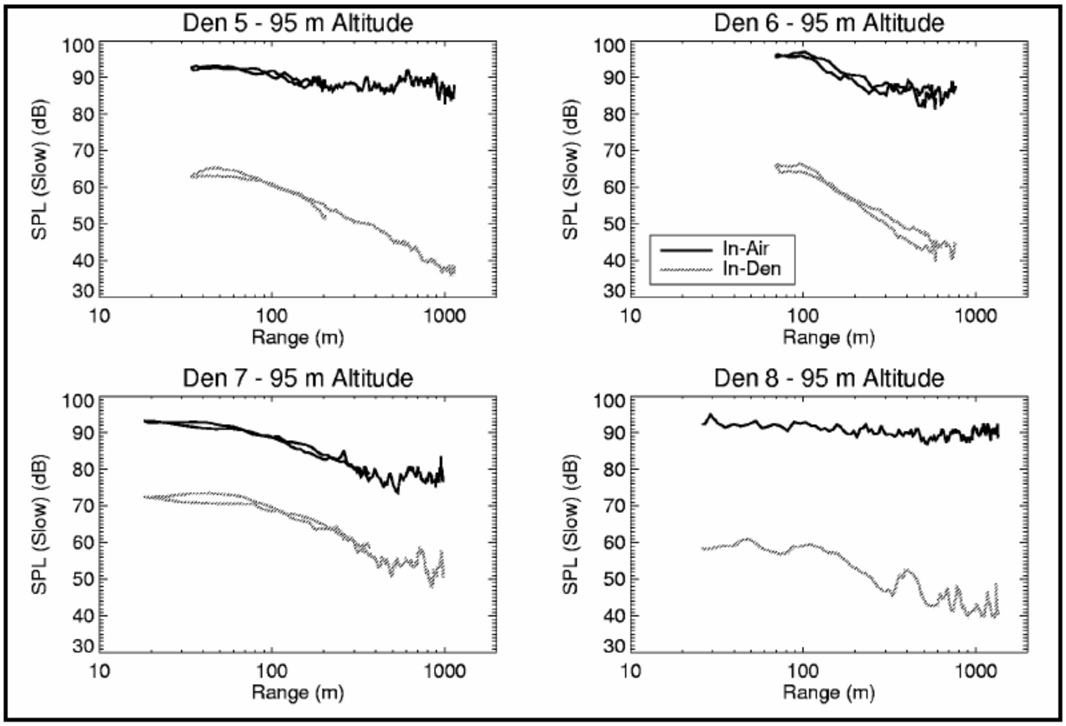

Figure 52: Sound pressure levels (dB re 20 μPa) from Bell 206 flying at 95 m altitude with mean airspeed 33 kph. Range axes are logarithmic.

5 DISCUSSION

In recent years, concern has been raised that industrial activities associated with oil and gas exploration and development on Alaska's North Slope may negatively impact polar bears, especially pregnant females and their denning habitat (Geraci and St. Aubin 1980, Lentfer 1990). Much of the heavy construction and exploration activities on the North Slope take place in winter to minimize disturbance to wildlife present in the area during the brief Arctic summer. Polar bears, however, are year-round residents of the North Slope and from December to April, noise and vibration from industrial activities may have the potential to disturb parturient females in natal dens (Amstrup and Gardner 1994).

Polar bears are known to den in close proximity to industrial activities. The noise-insulating properties of dens may be an important factor in reducing the disturbance to these bears. In 1991, two maternity dens were located on the south shore of a barrier island within 2.8 km (1.7 mi) of a production facility (Amstrup 1993). Both bears emerged with cubs at normal times, and the cubs of at least one of the bears were known to have survived for at least six months. Recently, denning female polar bears were found close to industrial activities on Flaxman Island. During winter 2000-2001, active dens were located within approximately 0.4 km and 0.8 km (0.25 mi and 0.5 mi) of remediation activities on Flaxman Island without any apparent impact to the bears. During March 2002, throughout the remediation project and during this study, a polar bear monitor checked 3 suspected and 1 known polar bear den on Flaxman Island daily. Den 821, located approximately 0.7 km SE of the G-2 reserve pit, was not abandoned during this study. The female from den 821 was first seen on 18 March 2002 with 1 cub and was last seen 20 March 2002 with no apparent impacts from industrial noises on the island.

The artificial dens used in this study resembled natural polar bear dens (Durner et al. 2003). We assume that these artificial dens provide a good measure of the noise-insulating properties of dens, and an indication of the noise and vibration energy that denning bears may experience as a result of industrial activities associated with oil and gas exploration and development on Alaska's North Slope.

5.1 Background Noise

Ambient noise is described as noise of natural and artificial origin that is present in the environment, not including noises from specific, identifiable sources. Ambient noise is variable, and depends on such factors as wind speed, wave action, seismic (natural) activity, precipitation, sea-ice action, and even molecular action at high frequencies. Our "ambient" measurements are in fact background levels because known industrial sources contributed to ambient conditions and we were not able to filter out this additional industrial contribution to ambient levels. In Arctic Alaska during the winter, wind speed is the primary factor affecting levels of background noise. Blackwell et al. (2003) measured in-air background broadband noise levels on Northstar Island to be 44 dB re 20 μPa. During this study, background noise was typically around 60 dB re 20 μPa and was highly correlated to wind speed (Appendix B). Inside the dens, the effect of wind is much reduced, background levels were typically near 30 dB re 20 μPa. However, despite the lack of wind inside dens, low frequency noise levels in the dens were found to vary by approximately 10-12 dB between times of high and low wind speeds. High frequency sounds are generally not present in the spectral distribution of background noise within the artificial dens. It is clear that some noise, mostly at mid to high frequencies, is attenuated by the amount of snow typically surrounding polar bear dens.

5.2 Industrial Noise

Industrial noise from oil and gas activities is highly variable and may include heavy equipment operation, seismic exploration, and drilling on land, sea ice or open water. During this study, remediation of an unused reserve pit included blasting a well casing, operations of heavy machinery, including a surface trimmer and bulldozer to break up contaminated soils, front-end loaders to gather contaminated soils and load them onto gravel haulers, Maxihaul earth movers to transport materials to disposal sites in the Prudhoe Bay complex, and the associated support vehicles (pick up trucks, fuel truck, etc.) necessary to support remediation activities.

5.3 Insulating Properties of Snow

5.3.1 Sound energy

The snow surrounding artificial polar bear dens was greatly attenuated sound propagation into the den. During both the active and inactive periods, the median broadband sound levels inside the dens were reduced by approximately 25-42 dB. In each case (active and idle) the den nearest the active pit was the noisiest, both inside and outside the den. It is clear that the noise was attenuated by distance, but was confounded by multiple sources due to the position of the dens between the camp and reserve pit G-2. In-air median broadband sound levels were reduced from 83 to 63 dB during the active period, and from 76 to 63 dB in the idle period. Wind speed and direction influence the ambient sound levels, but the snow effectively reduces the sound exposure of polar bears in their dens.

In addition to generalized construction noise, the snow reduced noise from vehicles passing along an ice-road near the dens. Vehicles traveling along the ice-road typically came within 12 m (39 ft) of the artificial dens, far closer than allowed under a Letter of Authorization from the USFWS (One mile is the default distance). Noise levels resulting from vehicle traffic were typically reduced by 25 dB inside the dens. The dens' ability to insulate against sound increased from 25 dB to 40 dB as frequency increased from 500 Hz to 1000 Hz. The ability of the dens to attenuate sound at higher frequencies was especially evidenced by the total attenuation of noise from 1000 Hz vehicle back-up warning beepers. Beeper noise that was more than 30 dB above background levels outside one den was reduced to below background levels (typically 25 – 30 dB) inside the den. Therefore, most high frequency sounds are unlikely to be detectable within a bear den under normal ambient conditions.

Broadband noise levels inside the dens decreased as the distance between vehicle and den increased. The maximum distance that vehicle noise was detected by the instruments above background inside a den was 2000 m for an empty gravel hauler. However, only one such measurement was noted, the second greatest range was 1000 m for noise from the Hägglunds tracked vehicle. All other maximum distances were less than 500 m. Blix and Lentfer (1992) reported that seismic exploration, drilling and transport noises were generally undetectable at distances greater than 100 m from artificial dens, considerably less than the 2000 m maximum detection reported here. The large variation in maximum detection distances may be a result of varying wind speed and direction, snowdrift depth, snow density, ceiling thickness, and den orientation relative to the road. Polar bears will naturally experience a wide range of noise levels caused by variations in wind speed and direction (Blix and Lentfer 1992). In addition, industrial sounds just above background levels are unlikely to result in biologically significant responses.

Audiograms to determine the frequency and sensitivity thresholds of polar bear hearing have not been determined. Although specific hearing thresholds have not been measured, bears have been observed to respond to some noises. In tests with non-denning grizzly bears (*Ursus horribilis*) and polar bears, sounds similar to natural bear sounds elicited behavioral responses (Miller 1980; Hunt 1984). In tests of acoustic deterrents on captive and wild non-denning bears, loud, sharp noises, such as an air horn and natural and synthesized aggressive bear sounds caused bears to move away from the noise source (Miller 1980; Wooldridge and Belton 1980). Frequency and amplitude were not measured for these sounds during the tests. Responses by individual polar bears to "loud" noises ("loud" was defined by the authors, not absolute levels) varied from no perceived behavioral change to temporary displacement. This suggests high variability of tolerance of individual bears to a given noise source is an important factor in evaluating the potential for disturbance. Indeed, Amstrup (1993) noted that some denning polar bears appeared to tolerate disturbances close to the den while other females appeared to abandon their dens, although he could not discern if the abandonment was caused by anthropogenic disturbance or natural causes.

The variability of within-den received noise levels from various vehicles suggests that some vehicles may be less likely to disturb polar bears in dens if an operator unknowingly approached a polar bear den. The Hägglunds tracked vehicle produced the loudest noise of the surface vehicles. It produced the maximum in-den noise levels and could be detected above background levels at 1000 m. In contrast, the Tucker Sno-Cat tracked vehicle produced significantly lower noise levels. Consequently, the Tucker Sno-Cat tracked vehicles may minimize disturbance to polar bears when traveling near known dens.

Helicopters are commonly used by industry and scientific investigators in the Arctic, and were the loudest noise sources measured during this study. The in-air noise from the helicopter was reduced by distance and altitude. Helicopter noise propagating in-air is strongly influenced by wind speed and direction, and number of blades, rotor pitch and angle, etc. (Richardson et al. 1995). In addition to the in-air noise attenuation for the Bell 206, sound levels within the dens decreased further as the helicopter increased distance from the dens. The maximum level measured inside the den was 82 dB re 20 µPa (flat – slow weighting) for the Bell 206 as it hovered 16 m directly above the den. The corresponding level outside the den was 110 dB re 20 µPa. The levels inside the den dropped to 76 dB, 68 dB and 58 dB as the elevation increased to 30 m, 60 m, and 130 m, respectively. These levels are well above background noise levels in the dens, typically 30 – 40 dB. Helicopter noise remained above background until the helicopters were greater than 1000 m distant (horizontally) from the dens. Little variation in the received levels was noted between passes at different altitudes. Again, the ability of the dens to attenuate noise was evident. The noise from helicopters was reduced by 29-31 dB even though the dominant frequencies of the helicopter noise were below 100 Hz.

Helicopter noise may disturb denning polar bears. Helicopter noise is composed of continuous engine noise and rapidly repeating impulse noise from the rotor blades (Richardson et al. 1995; Larkin et al. 1994). The use of helicopters as a research tool and the potential effects they have on wildlife populations have been documented in some studies (Klein 1973; Lenarz 1974; MacArthur et al. 1979; Miller and Gunn 1979, 1980; Harrington and Veitch 1992, Richardson et al. 1995; Patenaude et al. 2002), although none have investigated the effects of helicopter noise on denning polar bears.

Single engine Bell 206 helicopters are generally used in support of onshore industrial activities throughout the North Slope while the twin engine Bell 212 is predominantly used to support offshore industrial activities and polar bear researchers during the winter and spring. Noise signatures from the Bell 206 and 212 during our study simulating maneuvers conducted during polar bear research suggests that the Bell 212 and the Bell 206 produce similar broadband noise levels. However, a spectral analysis of the recordings indicates that noise from the 212 is concentrated at lower frequencies. Consequently, the smaller helicopter (206) may be more audible if the hearing sensitivity of polar bears is higher at frequencies above 50 Hz.

The extremely low frequency noise (most energy was concentrated at frequencies < 30 Hz) caused by the detonation of an 8.7 kg liquid nitromethane, was detectible in all monitored dens, but was not detectible above wind noise outside the dens beyond 500 m. Inside the dens, where wind noise is almost completely attenuated, the blast noise was approximately 30 dB above the ambient noise and would be detectible to bears if their hearing sensitivity extends to the low frequencies that characterized the blast. Interestingly, the in-den sound levels were only minimally attenuated with range. Peak blast noise levels in den 7 at 1283 m range were 74.4 dB, only 2 dB less than in den 5, where peak level was 76.5 dB at 504 m. This suggests that very low frequency noises, such as those produced by the blast, are detectable within dens at substantial ranges. However, the peak blast level at den 6, 887 m from the blast was 72.6 dB, nearly 2 dB lower than in den 7, despite being 396 m closer to the blast. Den 6 was constructed in a large drift, and had a ceiling thickness of 30 in., compared with 22 in. in den 7 and 18 in. in den 5. The additional 8 in. of snow above den 6 measurably reduced the levels of low frequency sound that entered the den. We hypothesize that dens constructed with ceilings thicker than 30 in. would further reduce the noise that enters the dens. However, we were unable to test this hypothesis during this study. Durner et al. (2003) reported mean snow depth of 28 in. (72 cm) above the main denning chamber, but high variability in snow depth over the chamber (range 10 to 400 cm) for polar bear dens he studied.

The low sound levels of the industrial noises received from vehicles and heavy equipment used in this study suggest that noise disturbance to denning polar bears would not result in physical hearing damage, such as a reduction in hearing sensitivity. Denning polar bears may be able to hear noises from outside the den and it is possible that noise could lead to a behavioral response. However, hearing thresholds of polar bears and the signal to noise ratio that might elicit a response are unknown.

5.3.2 Vibration energy

The well blast detonation produced significantly higher levels of vibration in the dens than vehicle traffic or heavy equipment, however the levels were still below the human detection thresholds. The single blast event produced peak ground (measured in the snow) velocities of 3×10^{-4} m/s in den 5 at 504 m distance, 6×10^{-5} m/s in den 6 at 887 m distance, and 7×10^{-6} m/s in den 7 at 1283 m distance. It is likely that perceptible ground vibration would have been noticed at closer ranges. Vibration levels at the same locations in the tundra indicated vibration magnitudes approximately 20% less than the corresponding measurements in snow. This effect is attributed to lower density of the snow.

Very little activity occurred in the A-1 pit during the ground vibration and sound monitoring periods. However, heavy equipment operated in reserve pit G-2 during most of this period. Measurable ground vibration levels occurred only at den 8, which was located approximately 50 m to 150 m from the operating equipment. The trimmer used to break up frozen gravel prior to its excavation produced the highest vibration levels. This machine produced maximum ground velocity of 3.5×10^{-6} m/s in Den 8, at a distance of 76 m. This velocity is still far below the threshold for detection by humans.

Vibration levels inside the dens caused by vehicle traffic and equipment working in the reserve pits were typically very low in comparison with threshold levels for human detection. The maximum ground velocity measurement recorded was 1.3×10^{-5} m/s, for the Hägglunds tracked vehicle at 18 m range. This velocity is approximately 100 times lower than the threshold of perception by humans (Rathbone 1963). These results indicate that the vibration source, frozen tundra, or some combination of the two is not conducive to propagation of ground vibrations.

5.4 Variability in Propagation

Ground vibration waves propagate both in the snow and tundra. The relatively thin snow layer (≤ 46 cm [18 in]), however, is not conducive to long-range propagation for these low-frequency vibrations. Consequently, the measurements of vibration in the snow and tundra at the den sites represented vibrations that had likely propagated through the tundra. The measurements consistently indicated slightly higher levels of vibration amplitude in the snow than in the tundra for P-waves and Rayleigh surface waves (for instance, figures 23 and 27). The fact that higher Rayleigh amplitudes were measured in the snow is expected because surface wave amplitudes decay exponentially with distance from the pressure relief surface (air-snow boundary). Higher P-wave amplitudes in the snow are attributed to the fact that particle velocity is proportional to pressure and inversely proportional to density and sound speed. P-waves incident from the tundra to the snow at grazing (near horizontal) incidence will penetrate evanescently into the snow. The pressure amplitude will be less in the snow than in the tundra, but this reduction of pressure is more than compensated by the lower density and sound speed of the snow. The end result is greater particle velocity in the snow.

6 SUMMARY

Noise and ground vibration data were collected inside artificially constructed polar bear dens on Flaxman Island in the vicinity of remediation activities involving the use of heavy equipment and blasting. Noise measurements were made inside and outside artificial polar bear dens to determine the absolute sound levels and thus potential noise exposure to denning bears. Comparisons between an outside microphone and in-den microphone data permitted an estimation of the sound-insulating properties of the dens themselves. Ground vibration data were acquired from sensors frozen into the tundra and in the snow of the den floors.

Specific measurements of noise and vibration were made for the following vehicle types: front-end loader, grinder, gravel hauler, fuel truck, pickup truck, Hägglunds tracked vehicle and a Tucker Sno-Cat. A single blast event, which was used to cut a well pipe following well plugging, was monitored. Noise and ground vibration data were also obtained for Bell 212 and Bell 206 helicopter fly-bys, hovering and landing operations.

The maximum distance vehicle noise was detected above background noise in the dens ranged from < 500 m to 2000 m. The in-den background noise levels for the artificially constructed dens were typically very low. Third-octave band levels were less than 40 dB in frequency bands below 100 Hz, and less than 20 dB for bands greater than 100 Hz. The Hägglunds tracked vehicle produced some of the loudest sound pressure levels recorded for the vehicles in this study, while noises generated from the Tucker Sno-Cat and pick-up trucks were hard to detect above in-air background levels. In this study, vehicle noise from sources less than 500 m from the den was detectable above average background ambient noise levels.

Helicopter noise was well above background levels in the den until helicopters were at least 1000 m from the den. The maximum level measured was 82 dB (flat – slow) for the Bell 206 as it hovered 16 m directly above the den.

Vibration levels inside the dens caused by vehicle traffic and equipment working in the pits were typically very low in comparison with detectable levels for human response. The maximum ground velocity measurement recorded was 1.3×10^{-5} m/s, for the Hägglunds tracked vehicle at 18 m range, which is lower than the threshold of perception by humans. The relatively thin snow layer did not appear to be conducive to long-range propagation of the low-frequency vibrations produced by vehicles and equipment. Consequently, the measurements of vibration in the snow and tundra at the den sites represented vibrations that had primarily propagated through the tundra.

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8 LITERATURE CITED

Amstrup, S.C. 2000. Polar bear. p. 133-154 *In* J.C. Truett and S.R. Johnson (eds.) The natural history of an Arctic oil field: Development and the biota. Academic Press: New York.

Amstrup, S.C. 1993. Human disturbances of denning polar bears in Alaska. Arctic 46(3):246-250.

Amstrup, S.C., and C. Gardner. 1994. Polar bear maternity denning in the Beaufort Sea. J. Wildl. Manage. 58(1):1-10.

ANSI. 1990. Specification for Sound Level Meters. *American National Standard, ANSI Standard S1.4-1983 (R 1990).* New York: American National Standards Institute, 1990.

Blackwell, S.B. and C.R. Greene Jr. 2002. Sound and vibration measurements during winter drilling at Northstar in early 2001. p. 3-1 to 3-25 *In*: Richardson, W.J. and M.T. Williams (eds.) Monitoring of industrial sounds, seals, and whale calls during construction of BP's Northstar Oil Development, Alaskan Beaufort Sea, 2001. (Draft, April 2002) Rep. from LGL Ltd., King City, Ont., and Greeneridge Sciences Inc., Santa Barbara, CA, for BP Explor. (Alaska) Inc., Anchorage, AK, and Nat. Mar. Fish. Serv., Anchorage, AK, and Silver Spring, MD. LGL Rep. TA2571-2.

Blix, A.S. and J.W. Lentfer. 1992. Noise and vibration levels in artificial polar bear dens as related to selected petroleum exploration and developmental activities. Arctic 45(1):20-24.

Bollinger G.A. 1971. Blast Vibration Analysis, Southern Illinois University Press. 132 p. ISBN 0-8093-0951-3.

CH2M HILL. 2000. Alaska State A-1 G-2 inactive reserve pits flare pits, and associated drilling waste closure plan. Rep. from CH2M HILL, Anchorage, AK for ExxonMobil Production Co., Anchorage, AK.

CH2M HILL. 2001. Interim monitoring plan for Alaska State A-1 and Alaska State G-2 inactive reserve pits. Rep. from CH2M HILL, Anchorage, AK for ExxonMobil Production Co., Anchorage, AK.

CH2M HILL. 2002. Alaska State A-1 G-2 inactive reserve pits flare pits, and associated drilling waste closure plan amendment. Rep. from CH2M HILL, Anchorage, AK for ExxonMobil Production Co., Anchorage, AK.

Clark, D.A, I. Stirling, and W. Calvert. 1997. Distribution, characteristics, and use of earth dens and related excavations by polar bears on the western Hudson Bay lowlands. Arctic 50(2): 158-166.

Durner, G.M., S.C. Amstrup, and K.J. Ambrosius. 2001. Remote identification of polar bear maternal den habitat in northern Alaska. Arctic 54(2): 115-121.

Durner, G.M., S.C. Amstrup, and A.S. Fischbach. 2003. Habitat characteristics of polar bear terrestrial maternal den sites in northern Alaska. Arctic 56(1): 55-62.

Fay, R.R. 1988. Hearing in vertebrates: a Psychophysics Databook. Hill-Fay Associates, Winnetka, IL.

Geraci, J.R. and D.J. St. Aubin. 1980. Offshore petroleum resource development and marine mammals: a review and research recommendations. Marine Fisheries Review 42(11):1-12.

Greene, C.R., Jr. 1997. Physical acoustics measurements. (Chap. 3, 63 p.) *In*: W.J. Richardson (ed.), Northstar Marine Mammal Marine Monitoring Program, 1996. Rep. from LGL Ltd., King City, Ont., and Greeneridge Sciences Inc., Santa Barbara, CA for BP Explor. (Alaska) Inc., Anchorage, AK, and U.S. Nat. Mar. Fish. Serv., Anchorage AK, for BP Explor. (Alaska) Inc., Anchorage, AK. 22 p.

Greene, C.R. Jr., M.W. McLennan, and R.W. Blaylock. 2000. Sound and vibration measurements during Northstar construction in early 2000. P. 4-1 to 4-31 *In*: W.J. Richardson and M.T. Williams (eds.), Monitoring of ringed seals and sounds during construction of BP's Northstar oil development, Alaskan Beaufort Sea, winter and spring 1999-2000: 90-day report. LGL Rep. TA2426-1. Rep. From LGL Ltd., King City, Ont., and LGL Alaska Res. Assoc. Inc., Anchorage, AK, for BP Explor. (Alaska) Inc., Anchorage, AK, and Nat. Mar. Fish. Serv., Anchorage, AK, and Silver Spring, MD. 107 p.

Harrington, F.H. and A.M. Veitch. 1992. Calving success of woodland caribou exposed to low-level jet fighter overflights. Arctic. 45:213-218.

Hunt, C.L. 1984. Behavioral responses of bears to tests of repellents, deterrents, and aversive conditioning. M.S. Thesis. Univ. of Mont., Missoula. 137 pp.

Klein, D. R. 1973. The reaction of some northern mammals to aircraft disturbance. Paper presented at the XIth Conference, International Union Of Game Biologists., Stockholm.

Kinsler, L. E., A. R. Frey, A. B. Coppens, J. V. Sanders. 1982. Fundamentals of Acoustics. John Wiley & Sons, New York, NY. 480 p.

Larkin, R.P., L.L. Pater, and J. Tazik. 1994. Effects of military noise on wildlife: a literature review. USACERL Tech. Rep. 95/21. Final Report to U.S. Army Constr. Eng. Res. Lab., Champaign, IL. http://nhsbig.inhs.uiuc.edu/bioacoustics/noise_and_wildlife.text.

Lenarz, M. 1974. The reaction of Dall's sheep to an FH-1100 helicopter (Arctic Gas Biological Report Series, Chapter 3.): Canadian Arctic Gas Study Ltd. and Alaskan Arctic Gas Study Company.

Lentfer, J.W. 1990. Workshop on measures to assess and mitigate the adverse effects of arctic oil and gas activities on polar bears. Marine Mammal Commission. 43 pp.

Linnell, J.D.C., J.E. Swenson, R. Andersen, B. Barnes. 2000. How vulnerable are denning bears to disturbance? Wildl. Soc. Bull. 28(2):400-413.

MacArthur, R. A., Johnston, R. H., and Geist, V. 1979. Factors influencing heart rate in free- ranging bighorn sheep: a physiological approach to wildlife harassment. Canadian Journal of Zoology, 57:2010-2021.

Miller, G.D. 1980. Behavioral and physiological characteristics of grizzly and polar bears, and their relation to bear repellents. M.S. Thesis. Univ. of Mont., Missoula. 106 pp.

Miller, F. L. and Gunn, A. 1979. Responses of Peary caribou and muskoxen to helicopter harassment, Prince of Wales Island, Northwest Territories, 1976-77 (Occasional Papers No. 40.): Canadian Wildlife Service.

Miller, F. L. and Gunn, A. 1980. Behavioral responses of muskox herds to simulation of cargo slinging by helicopter, Northwest Territories. Canadian Field Naturalist, 94:52-60.

Moulton, V.D. and M.T. Williams. 2000. Appendix B, *In:* Monitoring of polar bears during construction of ice roads for BP's Northstar oil development, Alaskan Beaufort Sea, 1999. Final Rep. from LGL Ltd., King City, Ont., and LGL Alaska Res. Assoc. Inc., Anchorage, AK, for BP Explor. (Alaska) Inc., Anchorage, AK, and Nat. Mar. Fish. Serv., Anchorage, AK, and Silver Spring, MD. xiv +153 p.

Patenaude, N. J., W. J. Richardson, M. A. Smultea, W. R. Koski, G. W. Miller, B. Wursig, and C. R. Greene, Jr., 2002. Aircraft sounds and disturbance to bowhead and beluga whales during spring migration in the Alaskan Beaufort Sea. Marine Mammal Science, 18:309-335.

Rathbone, T. C. 1963. Human Sensitivity to Product Vibration, Product Engineering, Aug. 5, 1963, pp. 73-77.

Richardson, W.J., C.R. Greene Jr., C.I. Malme and D.H. Thomson. 1995. Marine mammals and noise. Academic Press: San Diego, CA. 576 p.

Stirling, I. and D. Andriashek. 1992. Terrestrial maternity denning of polar bears in the eastern Beaufort Sea area. Arctic 45:363-366.

Wooldridge and Belton. 1980. Natural and synthesized aggressive sounds as polar bear repellents. pp. 85-92 *In*: C.J. Martinka and K.L. McArthur (eds.) Bears—their biology and management. Bear Biol. Assoc. Conf. on Bear Res. and Manage. 10-13 Feb. 1980. Madison, WI.

APPENDIX A.

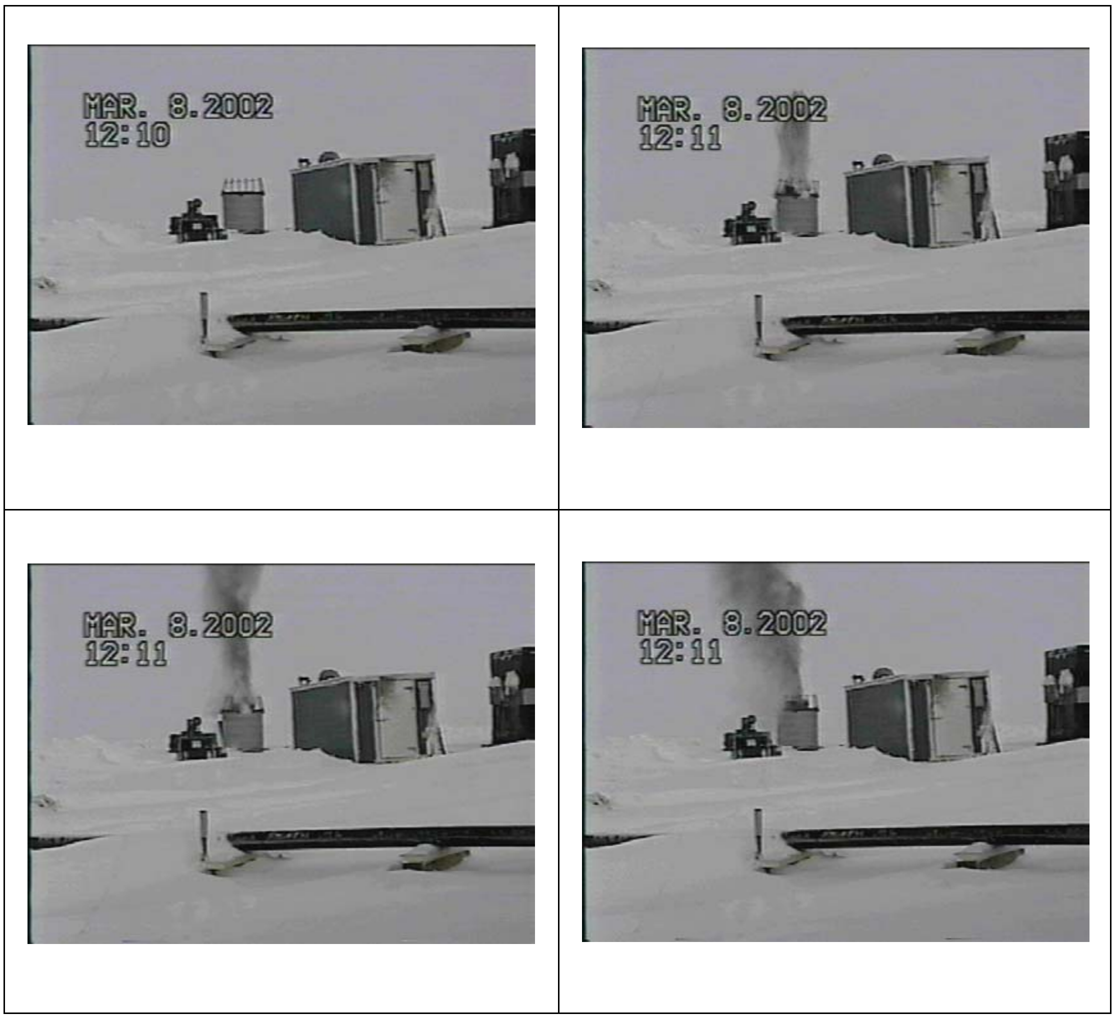

Figure A-1: Venting from well detonation.

APPENDIX B.

Figure B-1: BV206 tracked vehicle.

Figure B-2: Tucker Sno-Cat, loaded on a trailer.

Figure B-3: Photograph of a John Deere model 744H front-end loader.

Figure B-4: Full Kenworth Maxihaul used at Flaxman Island, March 2002.

Figure B-5: Bell 206 helicopter.