ADDENDUM D6K:

PUMP TEST SOP

November 2007

AQUIFER PROPERTIES TESTING
STANDARD OPERATING PROCEDURES
ADDENDUM D6K

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Acronyms and Abbreviations

°C	degrees Celsius
bgs	below ground surface
cfs	cubic feet per second
EPA	Environmental Protection Agency
°F	degrees Fahrenheit
ft	foot (feet)
gpd	gallons per day
gpm	gallons per minute
ISR	in situ recovery
MWPT	multi-well pump test
psf	pounds per square foot
psi	pounds per square inch
SWPT	single well pump test
WDEQ	Wyoming Department of Environmental Quality
WY	Wyoming

D6K.1 INTRODUCTION

The following discussion contains guidelines utilized by Hydro-Engineering LLC (HYDRO) for the performance and analysis of pumping tests to determine aquifer properties. Procedures and methodologies contained herein serve as a framework for designing, performing, and analyzing the results of a pumping test. As with many testing programs, these procedures must be adapted to the specific circumstances of the planned pumping test according to the engineering judgment of the user. This discussion does not include procedures for conducting slug tests or other aquifer properties testing methods that do not utilize a pumping system with a period of continuous discharge.

Procedures described in this document have been developed utilizing a variety of sources including: documented procedures (e.g. EPA, 1993 and U. S. Geological Survey Open-File Report 02-197, 2002), past experience in conducting pumping tests, and multiple references for ground water testing procedures. The presumption in this document is that well installation and completion techniques are already established, and that wells have been adequately developed.

D6K.2 AQUIFER PROPERTIES DEFINITIONS

Terminology and definitions related to pumping tests are included in the following discussion. This discussion is in summary form for the purpose of clarifying terminology used throughout this document, but is not a comprehensive review of all aquifer properties definitions.

An aquifer is defined as a water-bearing geologic unit capable of yielding water in economically usable quantities. An aquitard is a confining bed or unit that restricts or retards the flow of ground water and does not readily yield water. For most practical purposes, the orientation of both aquifers and aquitards is generally horizontal. An aquiclude is a geologic unit that prevents the flow of ground water (typically in a vertical direction through horizontal bedding).

The potentiometric surface is an imaginary surface representing the static head or level of ground water for a particular aquifer or aquitard. An aquifer is defined as confined if the potentiometric surface is above the top of the aquifer unit. An aquifer is defined as being unconfined or a water table aquifer if the potentiometric surface is within the interval of the aquifer unit.

Total porosity of a geologic material is the fraction of pore space within that material. Effective porosity is a measure of interconnected pore space and also reflects the size and shape of pores within the medium.

The ground-water conveyance properties of aquifer materials are defined by the hydraulic conductivity and/or transmissivity. The value of hydraulic conductivity indicates the volume of water that will move through a unit area of the aquifer in a unit interval of time under a unit hydraulic gradient. Hydraulic conductivity has units of length/time (L/T) and the term is often used interchangeably with coefficient of permeability. Transmissivity is the product of hydraulic conductivity and saturated aquifer thickness and has units of L^2/T.

The ground water storage properties are defined by the storage coefficient for confined aquifers and by the specific yield for unconfined aquifers. Both storage properties are dimensionless and reflect the volume of water yielded from or stored in a unit volume of the aquifer under a unit change in water level or head.

Static water level is the level to which water will rise in a well or piezometer in the absence of pumping or other withdrawals or injection of water in the area of the well. Drawdown is the difference between the static water level and the water level in a well after pumping has started. Recovery is the gradual return of the water level to the static water level after pumping has stopped. Residual drawdown is the gradually diminishing drawdown in a well that remains after pumping has stopped.

Boundaries may exist in an aquifer and are generally described as either recharge or low permeability boundaries. Recharge boundaries typically reflect streams, lakes, reservoirs, etc. which supply water to the aquifer. Low permeability boundaries can be created by a variety of geologic features including the limits of the permeable aquifer material, faulting etc., and they retard or prevent water flow in a generally horizontal direction.

D6K.3 TYPES OF PUMPING TESTS

Pumping tests are typically classified as single well or multi-well tests. A single well test involves only the well from which water is extracted. Multi-well tests require at least one pumping well and one or more observation wells.

D6K.3.1 SINGLE WELL PUMP TESTS

A single well pump test (SWPT) is used primarily to evaluate the yield, drawdown response, and performance of the pumping well. The testing can also be used to determine the hydraulic conductivity and transmissivity of the aquifer materials in the immediate vicinity of the well. In some cases, storage properties of the aquifer can be inferred from a SWPT, but these storage properties should be used with caution as they are much less reliable than storage properties determined from an observation well in a MWPT.

The typical SWPT includes pumping of a well while simultaneously monitoring water level in the well. Continued monitoring of the water level after pumping has stopped can also be valuable in determining hydraulic properties of the aquifer.

The simplest and most widely used approach for a SWPT is a constant discharge test where a relatively steady pumping rate is maintained throughout the pumping period. Variants of the SWPT include a constant drawdown test where the pump discharge is continuously adjusted to maintain a constant drawdown in the pumping well, and a step drawdown test where the discharge is deliberately increased at specified intervals. These variants of the SWPT are generally used to refine estimates of short-term and long-term yield for production water wells.

D6K.3.2 MULTI-WELL PUMP TESTS

A multi-well pump test (MWPT) is a more comprehensive test of aquifer and aquitard properties. In addition to the SWPT information provided for the pumping well, a MWPT can be used to evaluate storage properties of the aquifer, regional water conveyance (hydraulic conductivity and transmissivity) properties, continuity of the aquifer, the presence of barriers, and the hydraulic conveyance of overlying or underlying aquitards.

A typical MWPT includes a pumping well or wells and one or more observation wells. The water level is monitored in the observation well(s) and possibly the pumping well during the test. The observation well(s) can be completed within the same unit as the pumping well to evaluate aquifer conveyance and storage properties and to confirm continuity of the aquifer or the presence of boundaries. Observation wells can also be completed in adjacent strata to evaluate vertical continuity through aquitards.

D6K.4 BACKGROUND INFORMATION

The available geologic and well information should be compiled prior to the design of a SWPT or MWPT. This information should include but is not limited to: defining aquifer and aquitard strata; locations for available and proposed pumping or observation wells; well completion details for all available and proposed wells; the location and character of potential boundaries such as faults and streams; and available well yield estimates or measurements. Other useful information may include available water quality information, proximity to reliable pump power sources, installed pump performance curves, and acceptable water discharge procedures.

D6K.5 SINGLE WELL PUMP TESTS

The primary design criteria for a SWPT are the pumping rate and pumping duration. There are typically constraints imposed on the maximum pumping rate by the installed pump's performance, existing discharge pipe size, maximum pump size, available power supply, etc. The acceptable pump test duration is a function of pumping rate, aquifer type, aquifer thickness, proximity to any potential boundaries and intended usage of the results.

The type of SWPT conducted can also be influenced by the intended use of the well. In the case of water level or water quality monitoring wells, a SWPT is often conducted as a matter of opportunity during sampling or well development. In this case, the pumping rate and test duration criteria are relaxed. If the SWPT is required to evaluate well production, presence of boundaries, etc. the pumping rate and pumping duration should be more critically evaluated.

Attachment D6K-1 contains an example pump test form that can be used for both SWPT's and MWPT's. The available well information should be recorded for the pumping well in a SWPT. The critical records for analysis of well yield and aquifer properties are the water levels during and shortly after the pumping period, and the discharge during the test. If a transducer/data logger is used, the transducer pressure range, logger/channel number, setting depth, initial reading etc. should be recorded to allow processing of the transducer data.

D6K.5.1 REQUIRED MEASUREMENTS

The necessary measurements during a SWPT include: static water level, pumping start and stop times, water level changes, and discharge rate. Other relevant information that should be recorded includes: weather conditions during the testing, condition of the well, location and type of discharge, and methods of measurement. If the test duration is more than 12 hours and the stress rate is relatively low, it may also be informative to record barometric pressure changes during the test.

D6K.5.1.1 WATER LEVEL MEASUREMENT

The water level in the well should be monitored/recorded prior to, during, and immediately after the pump test. Acceptable methods for water level measurement are electrical continuity-based sounder (E-Tape), submersible transducer, or air line system. The E-Tape and submersible transducer are the preferred methods as they generally have much better resolution and accuracy than an air line system. Air line systems with precision pressure transducers or gauges can be used if the accuracy of the instrumentation is acceptable. Sonic or acoustic water level measurement devices should only be used if it can be demonstrated that the accuracy under the testing conditions is acceptable.

The preferred method of E-Tape or transducer operation is within a drawdown tube to isolate the water level measurement device(s) from cascading water or water surface disturbances. E-Tapes should be marked or be readable to the nearest 0.01 feet. If there is not a clearly marked measuring point on the well, the location where the measurement was taken should be recorded and the same measuring point should be used throughout the test. If a transducer is used to monitor the water level, the resolution of the transducer should be no greater than 2% of the total anticipated drawdown in the well.

The required frequency of water level measurements in the pumping well of a SWPT is subject to adjustment during testing. If the person(s) conducting the test are evaluating the drawdown while conducting the test, the frequency of measurements can be adjusted to produce sufficient measurements to allow analysis by the proposed methods. If the aquifer is unconfined, the early measurements may be important for accurate interpretation of transmissivity. In contrast, the analysis of transmissivity for a confined aquifer usually relies on measurements taken a few minutes or more after the pump start. If a transducer/data logger is used to monitor water level with a constant frequency, the frequency of readings should reflect the anticipated test duration and test conditions. Frequencies as high as once per minute can be used for short duration tests, while recording intervals of every 5, 15 or 20 minutes may be adequate for longer duration tests. Table D6K-1 presents guidelines for frequency of water level measurements. These frequencies can be adjusted during the test by the operator if warranted.

Table D6K-1. Guidelines for Water Level Measurement Frequency

Unconfined Aquifer		Confined Aquifer	
Time since Pump Start	**Measurement Frequency**	**Time since Pump Start**	**Measurement Frequency**
0 to 2 minutes	every 30 seconds	0 to 1 minutes	every 30 seconds
3 to 10 minutes	every minute	1 to 4 minutes	every minute
10 to 20 minutes	every 2 minutes	4 to 10 minutes	every 2 minutes
20 to 60 minutes	every 5 minutes	10 to 30 minutes	every 5 minutes
60 to 120 minutes	every 10 minutes	30 to 60 minutes	every 10 minutes
2 hours to 12 hours	every 30 minutes	1 hour to 2 hours	every 15 minutes
12 hours to 48 hours	every 4 hours	2 hours to 6 hours	every 30 minutes
after 48 hours	every 24 hours	6 hours to 12 hours	every 2 hours
		12 hours to 48 hours	every 4 hours
		after 48 hours	every 24 hours
Uniform Frequency with logger	Variable depending on test conditions	Uniform Frequency with logger	Variable depending on test conditions

If the data logger has the capability of variable water level measurement intervals, the programmed intervals can be adjusted to fit a logarithmic schedule that approximates the frequencies in Table D6K-1. Higher frequency of measurement is acceptable.

The pump test log should include records for water levels, discharge rates, and other relevant information (see Attachment D6K-1). There should be a date and time associated with water level and discharge rate measurements.

D6K.5.1.2 TRANSDUCER WATER LEVEL MEASUREMENT

If transducer/data loggers are used to record water level, the data recorded is subject to the type and manufacturer of the transducer. Transducers are available in a variety of configurations, but one of the more critical distinctions is whether the transducer is vented or non-vented. A vented transducer has a vent tube to allow equilibration of the reference pressure in the transducer with ambient atmospheric pressure. This allows the transducer to register a constant reading for a steady water level in a well under varying barometric pressure. The cable with a vent tube must be handled carefully to avoid pinching of the tube which can result in erroneous readings.

A non-vented transducer has a closed reference pressure and requires simultaneous measurement of barometric pressure in order to allow correction of the transducer readings for changes in barometric pressure. Individual manufacturers typically provide the companion barometric pressure instruments and incorporate the correction into operating software. For short-term tests of a few hours where changes in barometric pressure over the test period are small, it is not necessary to make this correction.

The format of data logger files is subject to the manufacturer's programming but should include, at a minimum, date and time of reading and a reading of depth of water over the transducer in known units. If a transducer/logger has provisions to input a setting depth, this feature can be utilized to provide direct output of water level. Post-processing of the data can also be used to convert the data to a usable format for analysis. Refer to the manufacturer's instructions for use of each transducer or logger.

The reading range of a transducer should correspond with the expected drawdown in the pumping well. If possible, the transducer range should be approximately 130% of the expected drawdown and the transducer should be set at a depth that is no more than 90% of the full transducer range. As an example, a transducer with a range of 100 feet can be set a depth of 190 feet in a well with a depth to water of 100 feet and a pump setting depth of 200 feet. If the expected magnitude of drawdown is small, the available transducer with the smallest range that is greater the expected drawdown should be used.

D6K.5.1.3 DISCHARGE RATE MEASUREMENT

The discharge rate should be monitored throughout the test. Acceptable methods for monitoring discharge include: instantaneous flow meters, totalizing flow meters, and timed capture of a known volume or weight.

Manual reading or electronic recording flow meters are acceptable. There are no significant restrictions on the type of flow meters that can be used provided the level of performance is acceptable. The recommended criterion for selecting and sizing a flow meter is that the meter be capable of measuring discharge from the well to within +/-10% of the smallest anticipated discharge during the test. The flow meter should also have a measurement range from 50% to 200% of the anticipated pump test discharge from the well. The frequency of discharge readings should be: a minimum of three readings per test, a reading following each discharge adjustment, and a reading corresponding to each manual water level measurement after the first 12 hours of the test. In order to determine discharge rate with a totalizing meter that does not have an instantaneous rate reading, the operator can take paired totalizing meter readings separated by a few minutes in time. If the totalizing meter reading is in gallons, the difference between sequential readings should be divided by the number of minutes separating the readings to determine the discharge rate in gallons per minute (gpm).

Timed capture of a known volume or weight can be used to determine discharge rate. This method for directing the discharge into the measurement container should not appreciably change the discharge rate. If valve setting changes are used to redirect the flow, the potential for changing the rate should be carefully evaluated. Pressure gages or visual observation can be used to evaluate potential discharge rate changes when redirecting flow for rate measurement. The volume of the container should be large enough that it takes 10 seconds or more to fill the container to a measured volume at the maximum flow rate. An example calculation for a 5 gallon capture volume over 17 seconds is as follows: the measured volume of 5 gallons is divided by a capture time of 17 seconds, and this quantity is multiplied by 60 to convert the reading to units of gpm. The result of this computation is 17.6 gpm.

D6K.5.2 DESIGN DISCHARGE RATE

The planned discharge rate for a SWPT is usually subject to a variety of constraints that may include: existing pump capacity, maximum practical pump size or power requirements, allowable discharge conditions, sustainable well yields, etc. Within these constraints, a guideline objective is to pump at a rate which results in drawdown over the test duration that is a significant fraction of the available drawdown. The available drawdown is equal to the depth of water over the pump intake. With preliminary estimates of well yield or aquifer transmissivity from well development or other testing, the planned discharge rate can be estimated using the Straight-Line method as described later in this document.

If a pump is installed or a portable pumping unit is used, the preferred pump setting is above or near the top of the screened interval to provide water flow past the pump motor. For wells where there is a large depth of water over the screened interval, the pump can be set at a depth that is slight greater than the maximum anticipated drawdown during the test. However, if the aquifer is unconfined or there is insufficient water depth above the screen, the pump should be set as deep as possible up to a few feet above the bottom of the well. If there are no other constraints for pump discharge sizing, a general guideline for desired pump capacity would be approximately 110% of the target discharge at a total dynamic head (tdh) corresponding to 80% of the available drawdown. This allows minor valve setting restriction to adjust the discharge without significant oversizing of the pump. However, this refined pump sizing requires substantial prior knowledge of the likely well yield and experience in pump selection and design. The more typical pump design would slightly oversize a pump using available estimates of well yield to allow operation at smaller rates if necessary.

If there is an existing pump in place or a portable pump unit with defined pump performance is used, the target drawdown over the test is a significant fraction of the available drawdown. However, the pump constraints may not allow testing to reach this objective. If the available pump is undersized, it should be operated at the maximum practical discharge. If the pump is grossly oversized and restricting the discharge to an acceptable rate could potentially damage the pump or discharge pipe, the pump should be operated at the minimum allowable rate and the test should be stopped when the water level is approaching the pump intake.

D6K.5.3 PUMP TEST DURATION

The duration of a SWPT can be adjusted according to the requirements of the analysis and the aquifer conditions. If the test is primarily to determine local aquifer transmissivity for a monitoring well, relatively short test duration may be adequate. The water level data can be evaluated during the test to determine if it is adequate for the intended analysis, and the test continued as long as necessary to produce the required data. If the well will be utilized as a production well, the duration of the test should be extended to refine the estimates of long-term well yield. SWPT durations of 30 minutes to 48 hours may be warranted depending on proposed usage of the well and the ratio of demand rate to available well yield. For a planned production well where the discharge demand is only a small fraction of the potential well yield, a test duration of a few hours should be sufficient. Conversely, if the discharge demand is approaching the maximum well yield, the SWPT duration should be extended as long as possible to determine sustainable yield.

Other factors that may affect pump test duration are the presence of boundaries or the effects of stratification within the aquifer. If the presence of a boundary is suspected, the data should be reviewed periodically and preliminary plots developed to evaluate the drawdown response. A distinct inflection point in the semi-log plots described later in this document is usually considered indicative of a boundary influence.

D6K.5.4 RECOVERY MONITORING

Following the cessation of pumping, the water level will gradually recover and approach the static water level in the well. Continued monitoring of this water level recovery may allow additional analysis of aquifer transmissivity by methods described later in this document. If the recovery data is be analyzed, the post pumping water level monitoring period should be at least as long as the pumping period. The frequency after the pump off time should generally correspond with the schedule listed in Table D6K-1 with the substitution of pump off time for pump start time.

D6K.6 MULTI-WELL PUMP TESTS

The design criteria for a MWPT include selection and location of pumping well(s), selection and location of observation well(s), pumping rate, and pumping duration. In addition to evaluating the aquifer properties and yield of the pumping well, a MWPT allows a more regional evaluation of transmissivity, determination of aquifer storage properties, evaluation of aquifer continuity, and evaluation of potential communication with adjacent aquifers..

If the selection and location of the pumping well is not dictated by other concerns or constraints, the pumping well should be centrally located within the testing area. The optimal distribution of observation wells is in a radial pattern surrounding the pumping well, but there are usually other constraints that govern the selection and location of observation wells.

D6K.6.1 WELL SELECTION

A variety of criteria are used in selecting both the pumping and observation wells. The pumping well should be selected to evaluate aquifer properties in the central area to be tested. Ideally, the pumping well should have sufficient yield to produce drawdown at selected observation well locations. The completion interval for the pumping well should also correspond with the desired testing interval. If the pumping well is partially penetrating, the correlation with completion intervals for observation wells should also be considered in well selection.

Observation wells can be selected to provide information about aquifer properties, heterogeneity of aquifer properties, continuity within the aquifer, communication with adjacent aquifers, or the influence of potential boundaries. For two observation wells completed within the same strata as the pumping wells, the preferred orientation of the observation wells is in an orthogonal configuration relative to the pumping well. This configuration generally provides the most refined estimates of directional transmissivity and/or distance to potential boundaries. Ideally, the observation wells should be located close enough to the pumping well to exhibit one foot or more of drawdown during the MWPT. The Theis equation described later in this document can be used to estimate the drawdown at observation wells for the planned pump test.

Observation wells completed in adjacent aquifers should be located as close as possible to the pumping well. This generally increases the likelihood that any vertical communication between aquifers will be revealed. An exception to this criterion occurs when there is faulting that can potentially connect adjacent aquifers across the fault. In this case, observation wells should be located across the fault and completed in intervals to evaluate potential communication across the fault.

Observation wells should also be located to evaluate potential boundaries. If a boundary may be present, the preferred observation well configuration would place a well on both the pumping well side and opposite side of the suspected boundary location.

D6K.6.2 REQUIRED MEASUREMENTS

The necessary measurements for the pumping well in a MWPT include: static water level, pumping start and stop times, water level changes, and discharge rate. Other relevant information that should be recorded includes: weather conditions during the testing, condition of the well, location and type of discharge, and methods of measurement. For most MWPT's with a duration of more than 24 hours, it is necessary to record barometric pressure prior to, during, and after the pumping period in order to correct the data for barometric pressure fluctuations. The necessary measurements for observation wells include water levels prior to, during and after the pumping period. The pump test forms in Attachment D6K-1 and Attachment D6K-2 can be used for recording of water level data for the pumping well and observation wells, respectively.

D6K.6.2.1 WATER LEVEL MEASUREMENT

The acceptable methods of water level measurement for a MWPT are basically the same as those for a SWPT. The preferred method of water level measurement for observation wells is with a transducer with at least one reference measurement with an E-Tape. The range and resolution of transducers for observation wells should correspond with the anticipated drawdown in the well if possible. A general guideline for selecting transducers for observation wells is to use a transducer with a range that is approximately 150% of the expected drawdown. If the expected drawdown is much smaller than the pressure range of available transducers, the transducers with the smallest pressure range should be used. The transducers should generally be set at a depth below the water level that is approximately 90% of the transducer range unless there is a rising water level trend or recovery from a previous test.

The required frequency of water level measurements in the pumping well after the pump start of a MWPT is generally the same as that listed in Table D6K-1 for a SWPT. The frequency of water level measurements in observation wells is dependent on several factors, including: distance to pumping well, correlation of completion intervals with the pumping well, and the presence of boundaries. The required water level measurement frequency for each observation well should be evaluated according to the preceding criteria. For observation wells located very close to (e.g. within 50 feet) and completed within the same strata as the pumping well, the measurement frequency after pump start should be similar to that of the pumping well. For more distant observation wells in the same strata as the pumping well, the interval between water level measurements can be increased in a manner that is generally proportional to the distance from the pumping well. A general guideline for uniform measurement intervals using transducers is 5 to 20 minutes depending on distance to the pumping well and the expected magnitude of drawdown in the observation well.

If the data logger has the capability of variable water level measurement intervals, the programmed intervals can be adjusted to fit a logarithmic schedule that approximates the frequencies in Table D6K-1. Higher frequency of measurement is acceptable.

The pump test log should include records for water levels, discharge rates, and other relevant information (see Attachment D6K-1). There should be a date and time associated with water level and discharge rate measurements.

D6K.6.2.2 PRETEST DATA

For MWPT's where there will be observation wells at a significant distance from the pumping well and the expected duration is more than 24 hours, it is advisable to collect water level data prior to the pumping period. This data can be used to identify prior trends in the water levels and to correct water level data for barometric pressure influences. These corrections may be appropriate for observation wells where the expected magnitude of drawdown over the test is small. The appropriate length of the pretest period depends primarily on the expected magnitude of drawdown in the most distant well and the existence of significant trends. Pretest periods of one (1) or more days are desirable if the drawdown response in distant observation wells will potentially be obscured by barometric or prior trend influences. In order to correct the water level data for barometric pressure influences, the barometric pressure must be recorded throughout the pretest period. The transducer water level measurement interval during the pretest period can typically be 15 minutes or more. The barometric pressure should be recorded hourly or more frequently during the pretest, pumping and recovery period.

D6K.6.2.3 DISCHARGE RATE MEASUREMENT

The discharge rate measurement criteria and methods for a MWPT are essentially the same as those for a SWPT. The duration of a MWPT is typically longer than a SWPT so discharge measurements should be distributed throughout the pumping period. Acceptable methods for discharge measurement are the same as those for a SWPT.

D6K.6.3 DESIGN DISCHARGE RATE

The criteria for selecting target discharge rate for a MWPT are basically the same as those SWPT. Ideally, the planned discharge rate would produce drawdown in the pumping well over the test duration that is a significant fraction of available drawdown. Like a SWPT, the range of available discharge rates may be subject to numerous constraints. The available drawdown is again defined as the depth of water over the pump intake. With preliminary estimates of well yield or aquifer transmissivity from well development or other testing, the planned discharge rate can be estimated using the Straight-Line method as described later in this document.

If a pump is installed or a portable pumping unit is used, the preferred pump setting is above or near the top of the screened interval to provide water flow past the pump motor. For wells where there is a large depth of water over the screened interval, the pump can be set at a depth that is slight greater than the maximum anticipated pumping well drawdown during the test. However, if the aquifer is unconfined or there is insufficient water depth above the screen, the pump should be set as deep as possible up to a few feet above the bottom of the well. If there are no other constraints for pump discharge sizing, a general guideline for desired pump capacity would be approximately 110% of the target discharge at a total dynamic head (tdh) corresponding to 80% of the available drawdown. This allows minor valve setting restriction to adjust the discharge without significant oversizing of the pump. However, this refined pump sizing requires substantial prior knowledge of the likely well yield and experience in pump selection and design. The more typical pump design would slightly oversize a pump using available estimates of well yield to allow operation at smaller rates if necessary.

If there is an existing pump in place or a portable pump unit with defined pump performance is used, the target drawdown in the pumping well over the test is a significant fraction of the available drawdown. However, the pump constraints may not allow testing to reach this objective. If the available pump is undersized, it should be operated at the maximum practical discharge. If the pump is grossly oversized and restricting the discharge to an acceptable rate could potentially damage the pump or discharge pipe, the pump should be operated at the minimum allowable rate and the test should be stopped when the water level is approaching the pump intake.

D6K.6.4 PUMP TEST DURATION

The duration of a MWPT is dependent primarily on the location and completion intervals for the available observation wells. For a pumping well with an adjacent observation well, acceptable test duration can plausibly be as short as an hour. A typical pumping duration for an ISR well field MWPT with observation wells at a distance of 500 or more feet from the pumping well is 72 hours or more. With most MWPT's, it is necessary to evaluate data during the test to determine if the drawdown response in the observation wells is adequate for the intended analysis. The magnitude of drawdown in observation wells where analytical techniques will be used to evaluate transmissivity and storage properties should be large enough that it is clearly distinguishable from natural fluctuations in water level. Regulatory testing requirements may also mandate a minimum magnitude of drawdown in specific observation wells. If necessary, the pumping period can be extended to increase drawdown at observation wells. For distant observation wells, the drawdown response will be lagged from that in wells closer to the pumping well, and the drawdown will generally continue for some period after the pumping is stopped.

D6K.6.5 RECOVERY MONITORING

Following the cessation of pumping, the water level in the pumping well and responsive observation wells will gradually recover and approach the static water level in the well. Continued monitoring of this water level recovery will allow additional analysis of aquifer transmissivity and storage properties by methods described later in this document. For typical analysis of recovery data, the post pumping water level monitoring period should be at least as long as the pumping period. In general, the frequency of transducer water level measurements for the recovery monitoring can be continued from the pumping period.

D6K.7 PUMP TEST ANALYSIS

The analysis of pump test data will be according to established and documented methods. The principle methods of analysis are the Straight-Line method, the Theis method, the Theis recovery method (see Ferris et al., 1962), and Hantush's Modified Method (Hantush, 1960). These methods are described within this section. More sophisticated methods will be used to evaluate aquifer properties under unconfined conditions, to correct for aquifer thinning, to correct for partial penetration, to analyze aquitard vertical permeability, and to evaluate the location of boundaries through image well analysis. Additionally, modified versions of the Theis method and the Straight-

Line method can be used for MWPT's with multiple pumping wells. For MWPT's with suitable observation well locations and completions, directional transmissivity of the aquifer may be evaluated using a method described by Papadopulos (1965).

D6K.7.1 THEIS EQUATION

Theis, in 1935, introduced his equation to determine drawdowns in a non-leaky, confined aquifer. The following is a general definition of the Theis equation:

$$T = \frac{114.6Q\,W(u)}{s}$$

$$u = \frac{2693r^2S}{Tt}$$

where: s = drawdown, in feet
Q = discharge, in gallons per minute (gpm)
W(u) = well function, the integral from u to infinity of $(e^{-u})/u\,du$
T = Transmissivity, in gal/day/ft
u = well function variable
r = observation well radius from pumping well, in feet
S = storage coefficient
and t = time since pumping started, in minutes

Pump test data are analyzed by matching the log-log plot of drawdown versus time to Theis' type curve [W(u) vs. 1/u] and applying the above equations to the match. Pages 92-98 of Ferris and others (1962) present a more thorough discussion of the Theis equation.

The value of the integral expression for W(u) is given by the following series:

$$W(u) = -0.577216 - \ln u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!}...$$

where all terms are as previously defined.

Theis' method is typically used for observation wells in a MWPT. Although the bore hole radius can be used as in input for the pumping well in a SWPT, the method is overly sensitive for a small radius and the resulting transmissivity and storage coefficient are of questionable utility for a pumping well. Theis' equation can also be used to estimate drawdown for the purposes of pump test design with preliminary estimates of transmissivity and storage coefficient.

D6K.7.2 STRAIGHT-LINE (JACOB) EQUATION

Jacob (1944) developed a simplified form of Theis' drawdown equation by truncating the well function series after the first two terms. Assuming the truncation, the following equations were developed to analyze drawdown versus time data on semi-log plots and is called the straight-line or Jacob equation:

$$T = 264\ Q[\log(t_2/t_1)]/(s_2 - s_1)$$

$$T = 264\ Q/\Delta s$$

$$S = T\ t_o/4800r^2$$

s_1 = drawdown, in feet, at time since pumping started, t_1, in minutes
s_2 = drawdown, in feet, at time since pumping started, t_2, in minutes

and $t_2 > t_1$
Δs = change in drawdown over one log cycle of time on a semi-log plot, in feet
S = storage coefficient
t_o = straight-line intercept of zero drawdown, in minutes
r = radius of well, in feet

A straight line is fitted to the semi-log plot of drawdown versus time (log scale) to obtain transmissivity. Jacob suggested the u values less than 0.01 are needed before his straight-line method is useful. However, a plot of W(u) versus 1/u on semi-log paper indicates that this method should be applicable for values of u as large as 0.1. Kruseman and de Rider (1991) suggest the use of a u of less than 0.1 to meet the Jacob condition. Pages 98-100 of Ferris and others (1962) may be consulted for additional information on Jacob's method.

D6K.7.3 THEIS RECOVERY EQUATION

Theis' equation can be modified to handle recharge of a well or multiple pumping periods by summation of the well functions. The following equation is the solution of Theis' equation for one pumping and recharge cycle (Recovery equation) of a non-leaky confined aquifer using a log-log match format:

$$T = 114.6\ Q\ [W(u) - W(u')]s'$$
$$u' = 2693\ r^2\ S/Tt'$$
$$T = 114.6\ Q\ [W(u) - W(u) + W(u')]\ sr$$
$$= 114.6\ Q\ W(u')/sr$$
$$s_r = s - s'$$

where: s_r = recovery, in feet
s' = residual drawdown (static water level – water level @ t'), in feet
W(u') = recovery well function

u' = recovery well function variable
t' = time since pumping stopped, in minutes

The recovery data sets are analyzed by matching the log-log plot of the recovery versus time since pumping stopped to Theis' type curve. The type curve variables are W(u') and 1/u' for the recovery match. The recovery is computed by estimating the drawdown which would have occurred if pumping had continued, and subtracting this predicted drawdown from the residual drawdown. For example, the recovery at 100 minutes after pumping has stopped is computed by estimating the drawdown had the pumping continued uninterrupted, and subtracting the estimated drawdown from the residual drawdown. The straight-line fit of the drawdown is normally extended to obtain these estimates of drawdown.

The well functions of the residual-drawdown form of Theis' equation were approximated by using the first two terms in the well function series. The following equations present the semi-log form of the Theis recovery equation:

T = 264 Q [log (t/t')]/s'
Or
T = 264 Q/Δs'

where:
t = time since pumping started, in minutes
t' = time since pumping stopped, in minutes
s' = residual drawdown, in feet
and
Δs' = change in residual drawdown over one log cycle of t/t' on a semi-log plot, in feet

Therefore, when residual drawdown is plotted on an arithmetic scale versus t/t' on a logarithmic scale, the above equation can be used for the straight-line fit (see Ferris, et.al, 1962, pages 100 through 102).

D6K.7.4 HANTUSH'S MODIFIED METHOD

Hantush (1960) presents a modification of the theory of leaky confined aquifers which had previously been described by Hantush and Jacob (1955). The modification took into account the storage of water in the semipervious confining bed. Equations developed are as follows:

$$T = \frac{114.6Q}{s} H(u, BETA)$$

where: H(u, BETA) = the integral from u to infinity of (e^-y)/y
[complementary error of the function of
(BETA/Square Root U) / Square Root (y(y-u))]dy

u = [(2693)r^2(S)]/Tt

And BETA = r/4b Square Root (K' Ss' / K Ss)

The main parameters are as follows:

	T	= transmissivity, gal/day/ft.
	Q	= discharge, gpm
	s	= drawdown, ft.
	y	= variable of integration
	r	= radius, ft.
	S	= storage coefficient
	t	= time, min.
	b	= aquifer thickness, ft.
	K	= aquifer permeability, ft/day
	K'	= confining layer permeability, ft/day
	Ss	= aquifer specific storage, 1/ft.
and	Ss'	= confining layer specific storage, 1/ft.

This form of the beta equation assumes all leakage is coming from only one of the two confining layers. Hantush (1961) presented tabulations of H(u, BETA) for varying values of u and BETA, and subsequently, a family of type curves showing H(u, BETA) vs. 1/u has been developed. Main aquifer properties can be determined by matching plots of observed drawdown versus time data to one of Hantush's type curves and using the equations presented above. The specific storage of the confining layer can be determined from laboratory measurements of the coefficient of compressibility and void ratio on a core of the aquitard, or estimated from the specific storage of the aquifer if the laboratory measurements are not available.

D6K.7.5 DIRECTIONAL TRANSMISSIVITY

Directional transmissivity of the aquifer was quantified using a method described by Papadopulos (1965). Papadopulos derived an equation for the drawdown distribution around a well discharging at a constant rate from an infinite horizontal anisotropic aquifer. Aquifer-test data from a minimum of three observation wells are analyzed to obtain principal transmissivities and the orientation of the principal axes.

The equations derived by Papadopulos for use in a type-curve matching technique are as follows:

$$s = \frac{114.6Q\ W(Uxy)}{\left[(Txx)(Tyy) - Txy^2\right]^{1/2}}$$

and

$$Uxy = \frac{(1.87S)}{(t)} \frac{\left[(Txx)(y^2) + (Tyy)(x^2) - (2Txy)(x)(y)\right]}{\left[(Txx)(Tyy) - Txy^2\right]}$$

Where: s = drawdown, in feet
Q = discharge, in gpm
W(Uxy) = well function
Txx, Tyy & Txy = transmissivity components, in gal/day/ft

Uxy = well function variable
S = storage coefficient
t = elapsed time, in days
x = distance from pumping well of observation well along arbitrarily selected x-axis, in feet

and y = distance from pumping well of observation well along arbitrarily selected y-axis (orthogonal to x-axis), in feet

For each of the three wells analyzed, observed drawdown data are matched against type curves to determine values of s, t, W(Uxy) and U(xy). Three equations with three unknowns are then solved simultaneously to determine the transmissivity components Txx, Tyy and Txy. Then principal transmissivities, Tee and Tnn, are calculated from the following equations:

$$Tee = \frac{1}{2}\left[(Txx + Tyy) + (Txx - Tyy)^2 + 4Txy^2\right]$$

and

$$Tnn = \frac{1}{2}\left[(Txx + Tyy)^2 + 4Txy^2\right]$$

where: Tee = maximum transmissivity
Tnn = minimum transmissivity

The angle between the arbitrarily selected x-axis and the axis of maximum transmissivity (θ) is then determined by the following equation:

$$\theta = \arctan(Tee - Txx)/Txy$$

D6K.8 SUMMARY

The preceding discussion of pumping test procedures and analysis provides guidelines for planning and conducting SWPT's and MWPT's. These guidelines must be adapted to the circumstances of the planned testing.

D6K.9 REFERENCES

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Attachment D6K-1. Example Pumping Well Pump Test Form

PUMP TEST FORM

				Project	
Pumping Well		Total Depth		Page	
Obs Well		MPE		Date	
Obs Well		Stick Up		Bar. Press (Y or N)	
Obs Well		Pump Setting		Bar. Press. File	
Obs Well		S.W.L		Transducer (Y or N)	
Obs Well		Pump Start Date		Transducer Range	
Obs Well		Pump Start Time		Logger No.	
Obs Well		Pump Stop Date		Logger Channel	
Obs Well		Pump Stop Time		Ini. Trans. Reading	

Date	Time	DTW	Discharge Rate	pH	Temp	Conductivity	Comment

Attachment D6K-2. Example Observation Well Pump Test Form

OBSERVATION WELL TEST FORM

				Project	______
Well Name	______	Pumping Well	______	Page	______
Total Depth	______	Pump Start Date	______	Transducer (Y or N)	______
MPE	______	Pump Start Time	______	Transducer Range	______
Stick Up	______	Pump Stop Date	______	Logger No.	______
S.W.L	______	Pump Stop Time	______	Logger Channel	______
				Ini. Trans. Reading	______

Comments:

Date	Time	DTW	Comment	Date	Time	DTW	Comment