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Appendix A-2

Overview of Aquifer Test Analysis Procedures and Tools Used

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This section describes the methods used to analyze the pump test data from both the Dewey and Burdock tests.

Determining Response

Water levels in each well were measured and recorded with vented In-Situ™ Level TROLL™ pressure transducers with built in data loggers. The pressure ratings for the transducers range from 100 to 300 pounds per square inch (psi). Transducer accuracy (in comparison to known pressure or other pressure reading devices) is stated by the manufacturer to be ±0.1 percent of full-scale reading (i.e., 100 to 300 psi), so the limit of accuracy varies from 0.1 to 0.3 psi, or about 0.2 to 0.7 ft. Transducer sensitivity is stated to be ±0.01 percent of full-scale, resulting in sensitivity limits of about 0.01 to 0.03 psi, or 0.02 to 0.07 ft.

Transducer response figures in the text (Figures 4.2 through 4.4 at Dewey and Figures 5.2 through 5.4 at Burdock) were made from graphs displaying raw transducer data produced directly from Win-Situ™ software provided by In-Situ with the rental transducers. The software should be publically available and can be used to read the binary data files that are provided on CD-ROM in Appendix E. The WinSitu™ software exported transducer data logger records to ".csv" text files with approximately 60,000 to 70,000 records for each well.

The Win-Situ graphs display complete drawdown and recovery data files that exceed the capacity of individual spreadsheets for display and storage. The pumping well data are repeated on some figures for reference as timing marks for the phases of the tests. The data at observation wells also exhibit spikes in the transducer temperature measurements when the data logging shifted from 10 second to 1 second intervals; these can be used to judge within ± 2 hours when the pump was shut off and recovery began at the pumping well.

Precise timing of responses is more clearly analyzed on spreadsheet log-log plots after the data are reduced to 30 points per log cycle (in seconds). The computer method to reduce the large text file to manageable time-drawdown data files is described in Section A.1-3 (above).

Theis Drawdown and Recovery Analysis

Drawdown data collected from all wells were graphically analyzed to determined aquifer properties of transmissivity and storativity using the Theis method (Driscoll, 1986, and numerous other references).

Assumptions for the Theis Method

At observation wells, the Theis method is mathematically valid for all distances and times during the drawdown phase of a test, and there is general agreement about interpretation of deviations of drawdown data from Theis type curves in terms of features such as barrier boundaries and leakage from an overlying leaky aquifer (Kruseman and de Ridder, 1991).

The following simplifying assumptions underlie the Theis analysis (Driscoll, 1986):

- The water-bearing materials have uniform hydraulic conductivity (i.e., are isotropic) within the radius of influence of the well (i.e., the aquifer has infinite extent for the analysis).
- The aquifer is confined and not stratified.
- The aquifer thickness is constant.
- The pumping well is 100 percent efficient.
- The intake portion of the well penetrates the entire aquifer; well diameter is small so well bore storage is negligible.
- The potentiometric surface has no slope (perfectly horizontal).
- Laminar flow exists throughout the radius of influence of the well.

These assumptions are rarely completely satisfied in any pumping test. A first-order violation of the ideal test assumptions for the Powertech pumping test is partial penetration: at Dewey, the lower Fall River pumping and observation wells have 15-foot well screens within an approximate 85-foot sandstone zone within an approximately 160-foot thick sandstone-shale formation; at Burdock the lower Lakota pumping and observation wells have 10-foot well screens within an approximate 35-foot sandstone zone within an approximately 170-foot thick sandstone-shale formation

Secondly, the variegated sandstone-shale lithology clearly responds hydraulically in an anisotropic manner both laterally and vertically. It was determined with Powertech during the test design that an investigation of lateral aquifer anisotropy using four-well

triangulation was not warranted. The test design did investigate vertical anisotropy within each aquifer.

Pumping Test Design and Objectives

As noted in the pumping test work plan, (Knight Piesold, 2008), interpretation of test results with the above non-ideal conditions may result in uncertainties in the estimated transmissivity and storativity values. Reasons for conducting the 2008 tests with conditions contrary to the Theis assumptions were as follows:

- Powertech expects that the operational well field screens will be completed in ore, and the thickness of the ore determines the screen interval.
- The pump test was designed to see what flow could be expected in the wellfield.
- There are multiple ore zones (e.g., three ore zones in the Fall River at Dewey) and each one will have its own well screens, so one ore zone was picked to test.
- At new mines there are usually two pump tests, one to get regional aquifer characteristics and a second one to test the ore zone characteristics.
- The previous TVA tests constitute regional tests and had already been successfully conducted using pumping and observation wells more closely fully penetrating the entire aquifer.
- In comparison with the TVA tests, these newer tests would offer valuable differential diagnostic information.

Theis Analysis Methods

Theis analysis was initially performed in spreadsheets developed by Knight Piesold that allow interactive entry of transmissivity and storativity to calculate the dimensional version of the type curve that matches time-drawdown data (e.g., Figures 4.5 and 5.5 in the text). Theis analysis was expanded to use using automated curve matching in commercial AquiferWin32^{TM} software (ESI, 2003). The software also performed Hantush-Jacob drawdown analysis as described in the text. In automated drawdown analysis samples are weighted as follows: samples before the first response are ignored, and samples after the first occurrence of the barrier or leakage boundary are ignored.

The AquiferWin32^{TM} software was also used to analyze recovery data with the straight-line Theis recovery procedures, with theoretical considerations described in greater detail below. Samples are weighted according to (1) the theoretical criterion that u' be < 0.01, which restricts the data to later-time (to the left on the t/t' axis); and (2) the portion of the recovery before the change in slope due to a barrier or recharge boundary is used. Data

not satisfying u' < 0.01 or obtained after a boundary was encountered were weighted to be ignored.

The analysis of data from the pumping wells is complicated by well losses due to well inefficiency, partial penetration effects, and drawdown modified by borehole storage. This is accounted for in Theis drawdown analyses by fitting just the later time data (at pumping wells) to the type curve. This is done with the AquiferWin32™ software by assigning sample weights to data after the time at which borehole storage becomes negligible.

Driscoll (1986) provides an empirical formula for determining the time at which borehole storage effect become negligible, as follows:

$$tc = 0.6\ (dc^2 - dp^2) \text{ divided by } Q/s$$

Where tc is time in minutes, dc is the inside diameter of the well casing in inches, dp is the outside diameter of the pump column pipe in inches, and Q/s is the specific capacity of the well in gpm per foot of drawdown at time tc. Calculated times were 21 minutes for the pumping well at Dewey and 50 minutes at Burdock.

Theis-Cooper-Jacob Straight-line Analysis

Spreadsheets are published by the U.S. Geological Survey (USGS) with sophisticated programming for the analysis of aquifer test data (Halford and Kuniansky, 2002). These were used for most straight-line analyses of the tests.

Straight-line Drawdown Analysis

A USGS spreadsheet for drawdown analysis with the Cooper-Jacob straight-line approximation was used for the drawdown phase at the pumping wells. Another USGS spreadsheet programmed for Theis Recovery analysis with the straight-line approximation was used to analyze the recovery data at all wells.

The Theis method is linearized with the Cooper-Jacob straight-line approximation (Halford and Kuniansky, 2002). The approximation is only valid at later times as determined by u or u', the relationship of aquifer parameters with distance from the pumping well (r) and elapsed time t or t' (where t and u refer to the time from the start of pumping and t' and u' to the time from the cessation of pumping), as follows:

$$u \text{ or } u' = (r^2 \times S) \div [4 \times T \times (t \text{ or } t')] \text{ and } \quad u \text{ or } u' < 0.01.$$

For a pumping well the distance becomes the radius of the casing (r_c) which is small, and to obtain a time criterion (t_c or t_c' where the straight-line approximation is theoretically valid), the above relationship is inverted by setting u or u' <= 0.01 and S = 1 x 10^{-4}, yielding (Halford and Kuniansky, 2002):

$$4 \times (t \text{ or } t') \times 0.01 >= r_c^2 \times 10^{-4} \div T$$
$$t_c \text{ or } t_c' >= 100 \times r_c^2 \div (4 \times T)$$
$$t_c \text{ or } t_c' >= 25 \times r_c^2 \div T$$

The calculation of t_c or t_c' gives a criterion for theoretically valid data at the pumping well in terms of time, and similarly for u or u' for observation wells. In this report only transmissivity is determined by the straight-line methods. The drawdown phase and Theis or Hantush-Jacob type-curve analysis are used to determine storativity. To calculate u or u' at observation wells, the storativity result from the drawdown phase is used. At the pumping wells, a storativity of 1 x 10^{-4} is assumed.

The USGS spreadsheet allows interactive determination of transmissivity by moving the yellow endpoints of the red line to match the desired slope (see red lines between yellow endpoints on Figures 4.7 and 5.7 in the text). The USGS spreadsheet has been modified to also calculate the value of u or u' and t_c or t_c', and the length of the straight line has been manually set on the figures to approximately correspond to data ranges where the critical values are met. The figures thus indicate the data where the straight-line solutions are theoretically valid, which aids in visually determining which portions of the plots to use for analysis.

The analysis of data from the pumping well is complicated by well losses due to well inefficiency, partial penetration effects, and drawdown modified by borehole storage. The straight-line approximation with the t_c criterion described above is used in the USGS spreadsheet to select the late-time data during the drawdown phase at pumping wells. This is because at later times borehole storage and partial penetration effects are eliminated and change in drawdown and the straight-line slope are due to aquifer transmissivity rather than the fixed offset due to well losses (Halford and Kuniansky, 2002). The USGS spreadsheet determines transmissivity and well efficiency, with the efficiency based on the theoretical drawdown with the assumed storativity of 1.0 x 10^{-4}.

Straight-line Recovery Analysis

The analysis of recovery data involves the measurement of the rise in water levels referred to as residual drawdown. The method determines the Δs', the change in residual drawdown over one log cycle of t/t', where t is the time from the start of pumping and t' is the time from the cessation of pumping. Figures 4.7 and 5.7 in the text illustrate the Theis recovery analysis at the pumping wells. On each recovery analysis figure the data range where the t_c' or u' criteria is satisfied (see red lines between yellow endpoints on Figures 4.7 and 5.7 in the text) are indicated together with the transmissivity reported by the USGS spreadsheet.

Distance Drawdown Analysis

Distance-drawdown analysis (Driscoll, 1986) was performed to determine average aquifer parameters using all appropriate observation wells simultaneously and also to determine a pumping well efficiency. The distance drawdown analysis relies on the same Cooper-Jacob straight-line approximation as described above, although according to Driscoll (1986) the value of u can be as great as 0.05. The value of u is calculated using the storativity of the observation wells determined in the Theis drawdown analysis. The aquifer parameters are determined by calculating Δs, the change in drawdown along the straight line over one log cycle, and r_0 which is the intercept at zero drawdown.

On a linear graph (see top portions of Figures 4.8 and 5.8 in the text), plotting the maximum drawdown in observation wells at the same time should map a profile of the cone of depression surrounding the pumped well. On a semi-log graph (bottom portions of Figures 4.8 and 5.8 in the text) there should theoretically be a straight line through the data points, except at the greatest distance from the pumping well where u is likely to be > 0.05 (Driscoll, 1986).