Aquifer Test Analyses, DOI-04-1a Well, Fort Yukon

Chapter C.

By Edwin P. Weeks and Arthur C. Clark

[1] Corresponding author, U.S. Geological Survey, Denver, Colorado.
phone: (303) 236-5797 barker@usgs.gov

[2] U.S. Geological Survey, Denver, Colorado.

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Introduction

An exploratory bore hole was drilled to evaluate the potential for the development of coal bed methane as an energy supply at a site just east of the Fort Yukon Long Range Radar Station in the late summer of 2004. The bore hole was originally drilled to a depth of 1283 feet in 1994 to obtain core materials for paleoclimate analysis (Tom Ager, written communication, 1994). In 2004, the hole was reoccupied and drilled to a total depth of 2287 feet. Coring in 1994 encountered a thick lignite bed at a depth of 1257 feet, and drilling was halted after 25 feet of lignite had been cored. The remaining thickness of this lignite, extending from 1283 to 1317 feet, was cored and analyzed for gas content. Another significant lignite seam, extending from 1900 to 1920 feet, was also cored and analyzed for gas content. The shallower lignite seam has slightly higher methane content and is substantially thicker than the lower layer. Hence, an attempt was made to finish the bore hole as a production well in the shallower lignite bed, followed by performance of an aquifer test. Events described below precluded a true aquifer test, but several sets of recovery data were collected during the development phase, four of which were analyzed to provide estimates of the lignite hydraulic properties.

Hydrogeologic Setting

Geologic details concerning this bore hole are provided in Chapter B, but hydrogeologic features relevant to hydraulic testing are briefly summarized here. The well penetrates about 100 feet of coarse surficial gravel deposited by the Yukon River, and deeper deposits tapped by the well consist of lacustrine deposits of interbedded clay, silty clay, silt, silty sand, and sand, with occasional lignite beds. Permanent permafrost extends from about 25 to 300 feet, providing a hydrologic confining layer for the underlying materials. The main interest of this hydrologic investigation is of the tested lignite bed and the beds immediately above and below it, as shown in Figure 1A. Briefly, the lignite is immediately overlain by a thin clay bed, separating it from a sand bed. A thicker clay bed separates the main lignite bed from an underlying thinner lignite that is in turn

underlain by another thick clay bed. These overlying and underlying clay beds should provide hydrologic confinement for the lignite, allowing well test theory developed for confined aquifers to be applied.

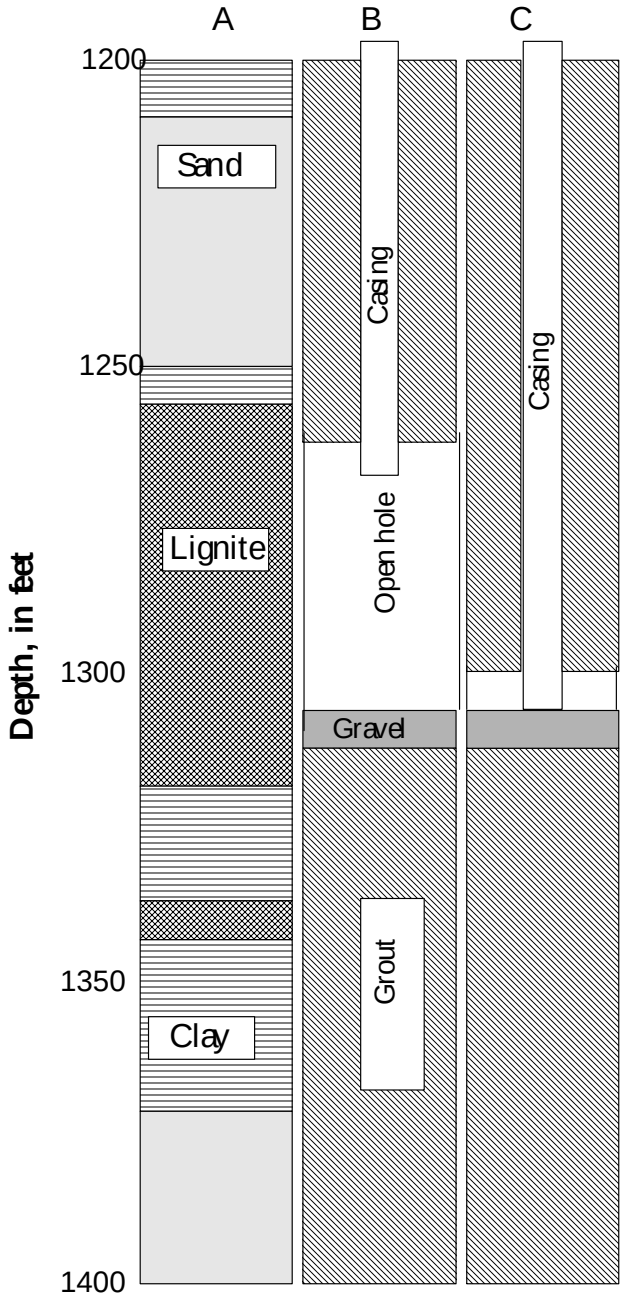

Figure 1. A. Geologic profile for 1200-1400 ft depth, B. Original well construction, C. Well configuration after the casing had slipped downhole by 35 feet

Well Completion and Initial Development

To complete the well for testing, the bore hole below the base of the upper lignite was backfilled with Volclay™ abandonment grout mixed with thick bentonite, bentonite pellets, and bentonite chips to a depth of 1313 feet, about 4 feet above the bottom of the lignite seam, providing the bottom depth that would yield water to the well. Gravel was added to a depth of 1307 feet to prevent bentonite from being pumped up into the planned open-hole interval. The lead section of well casing was equipped with five 6-in. shale baskets attached 7 feet above the bottom of a stainless steel tail section coupled to the 2.5-in. Schedule 80 PVC pipe, used to case the well. The casing was hung from a surface clamp at land surface so that the shale baskets (packer) bottomed at 1265 feet, about 8 feet below the top of the lignite. Including the open hole surrounding the tail pipe and the 6-ft gravel-filled section, the well section open to the lignite should have been 48 feet. Ten buckets of bentonite pellets were placed by tremie pipe immediately above the shale baskets, and the remainder of the annulus around the well casing was filled with abandonment grout. Details of well completion through the 1200-1400 foot zone are illustrated in Figure 1B.

Following completion of the well installation, drilling mud remaining in the open-hole portion of the hole (1265-1307 feet) was flushed with fresh water using a tremie pipe installed to a depth of 1302 feet. The driller reported that 400 gallons of fresh water were pumped down the casing before mud began to flow at land surface. The loss of this fluid may have resulted in additional formation damage and the apparent large skin effect described below.

Well Tests and Slug Test Theory

Following completion of the well, air-lift pumping was initiated to remove fines from the invaded zone surrounding the well bore in anticipation of the performance of an aquifer test. Several brief sets of recovery data were collected at various stages of development to provide data for test planning, but various problems occurred during development, described below, that precluded conducting the aquifer test. However, data for three of

the recovery data sets, as well as head recovery following the end of development were analyzed using slug test theory to obtain estimates of the hydraulic properties of the lignite bed.

The slug test theory used was that of Cooper et al. (1967), as modified by Butler (1997, p. 173) to account for the effects of well-bore clogging or development (well skin). The analysis procedure was also modified to that of Earlougher (1977, p. 99) to better analyze data that represent water level recovery of only a few per cent of its initial drawdown.The analysis relies on matching test data to a selected member of a family of theoretical log-log type curves of $1\text{-}H/H_0$ vs. KDt/r_c^2 for various values of $\alpha*$, defined as (Butler, 1997, p. 173): $\frac{r_w^2 S}{r_c^2}\exp(-2s)$,

where H is the remaining water level displacement, L; H_0 is the initial (instantaneous) water level displacement, L; K is aquifer hydraulic conductivity, L/T; D is screen or open hole length, L; t is elapsed time since the instantaneous displacement, T; r_c is casing radius, L; r_w is the open hole radius, L; S is the aquifer storage coefficient; and s is dimensionless skin. Dimensionless skin is defined (Matthews and Russell, 1967, p. 19-21) as $\left(\frac{K}{K_s}-1\right)\ln\left(\frac{r_{skin}}{r_w}\right)$,

where K_s is hydraulic conductivity of the clogged annular layer surrounding the borehole, L/T; and r_{skin} the outside radius of the clogged layer, L. In theory, transmissivity, T, equal to Kb, where b is aquifer thickness, should be the parameter determined by slug test analysis. However, practice indicates that the T determined from slug tests represents the KD product, indicating that, at the scale of the slug test, flow to the well bore is governed by the screen or open-hole length, rather than by the full aquifer thickness (Butler, 1997, p. 52-53).

For analysis, a data plot of $1\text{-}H/H_0$ vs. t, as determined from measurements, is prepared to the same scale as the type curve plot. To match the curves, values of $1\text{-}H/H_0$ for the data plot must coincide with those for the type curve family, but the logarithmic data time axis is shifted, by use of a multiplier M to provide a match of the data to a selected

member of the type curve family. M is equal to $\left(\frac{KDt}{r_c^2}\right)/t$, where $\left(\frac{KDt}{r_c^2}\right)$ is the type curve match point value as read from the x axis, and t is the time at which the match data point was read. M has the unit of T^{-1}. KD is then found as $KD = Mr_c^2$. Selection of the type curve to be matched can be quite subjective, as the type curves are of nearly constant shape over a significant range of $\alpha*$ values.

Hydraulic conductivity, K, is widely used by hydrogeologists as the hydraulic property governing the movement of water through porous media. However, because of the need to consider the flow of various fluids through porous media, petroleum engineers generally use permeability, k, in units of Darcies, as the parameter governing porous media fluid flow. As this practice has been followed in most of the literature on coal-bed methane development, k values will also be presented. A permeability of one ft/d is equivalent to 0.56 Darcy at the temperature of 4 °C prevailing at the depth of the lignite bed.

Test Data

Recovery data were either collected by use of an electric tape, by which DTW (depth to water) was measured directly, or by use of two absolute pressure transducers, one (an In Situ Minitroll™ transducer) emplaced at some depth below the water surface in the well and the other (an In Situ Barotroll™ transducer) at land surface to record barometric pressure. For the transducer data, DTW was computed as (DT-[TR-BP]) where DT is depth of emplacement of transducer below land surface, TR is the transducer pressure reading, feet of water, and BP is barometric pressure in feet of water (from the Barotroll transducer). For all tests, the SWL (static water level) was assumed to be 6 feet below land surface, based on the approximate depth to water after the well was thawed in May 2005. Starting times for each test were assumed to coincide with the time at which air-lift pumping was stopped to allow for the test. This represents an approximation, as slug test theory assumes instantaneous displacement of the initial water level, whereas air-lift pumping for development was occurring for from a few to several hours prior to each water-level measurement period. However, in each case,

the period of air-lift pumping was small relative to the time required for full water level recovery, and the assumption of instantaneous displacement was assumed to be adequately met. The initial head displacement was assumed to be the DTW when pumping was stopped minus the SWL. However, heads were not monitored during air lift, so the initial DTW was estimated by linearly extrapolating the average rate of head increase during the test back to the start time. For each of the short recovery tests, the rate of head recovery was quite uniform with time, so this extrapolation should create little error.

Test 1

This data set is the first relable one available and was collected after the casing had been evacuated of water by air-lift pumping to a depth of 500 feet. Evacuation was accomplished in stages, beginning with a 200-foot evacuation starting at 08:18 on 09/07. Measurements of recovery of the water level for this evacuation were made with an electric tape, but the readings were later recognized to have been affected by water running down the casing, and hence were not reliable. The casing was evacuated in two additional stages to a depth of 500 feet, and recovery was again measured, after pumping halted at 11:30. This time, the problem of false readings was noted after a false start, and a series of six good measurements was obtained, beginning at 11:43:15, and lasting about 6 minutes. These data constitute test 1, which is the only test available for the full open hole thickness of 48 feet. The water level at 11:30 was computed to be 496 feet (rounded) by assuming that the average recovery rate of 0.86 ft/min. extended over the preceding 13.25 minute interval. Subtraction of an assumed SWL (static water level) below land surface of 6 feet provides an H_0 value of 490 feet. The length of drained column at each time t was computed as DTW-SWL.

Time	DTW (Depth to Water)	Elapsed time, sec.	H/H_0
11:43:15	485.	795	0.9776
11:44:25	484.	865	0.9755
11:45:36	483.	936	0.9735
11:46:45	482.	1005	0.9714
11:47:53	481.	1073	0.9694
11:49:01	480.	1141	0.9674

Table 1. Water-level recovery following evacuation to 500-foot depth 09/07

Data for test 1 are shown as the open triangles in Figure 2. Also shown are type curves for $\log_{10} \alpha*$= -4, -9, -15, and -30. For the test interval, both the data and the type curves form straight lines, with slope of the type curves increasing with decreasing $\alpha*$. Data for test 1 match the type curve for $\alpha*=10^{-9}$ reasonably well. This match was achieved by multiplying the data curve t values, which are in days, by 11.3, so $11.3day^{-1} = \frac{KD}{r_c^2}$.

Simplifying, KD=11.3 r_c^2/day, and, for the 1.125-in. (0.09375 ft) r_c, KD=0.1 ft^2/d. For the 48-ft thick open-hole section, K =2X10^{-3} ft/d. This value translates to a permeability of about 1.1 mD (milliDarcy) (Table 2).

Test	T, $ft^2/dX10^{-2}$	K, $ft/dX10^{-3}$	k, millidarcies	b, ft
Type Curve $\alpha*=10^{-4}$				
1	3.1	0.6	0.3	48
Type Curve $\alpha*=10^{-9}$				
1	9.9	2	1.1	48
2	1.8	1.4	0.8	13
Type Curve $\alpha*=10^{-30}$				
1	30	6	3.4	48
3,4	0.9	1.5	0.8	6?

Table 2. Results of slug-test type curve analyses for tests performed on the Fort Yukon well.

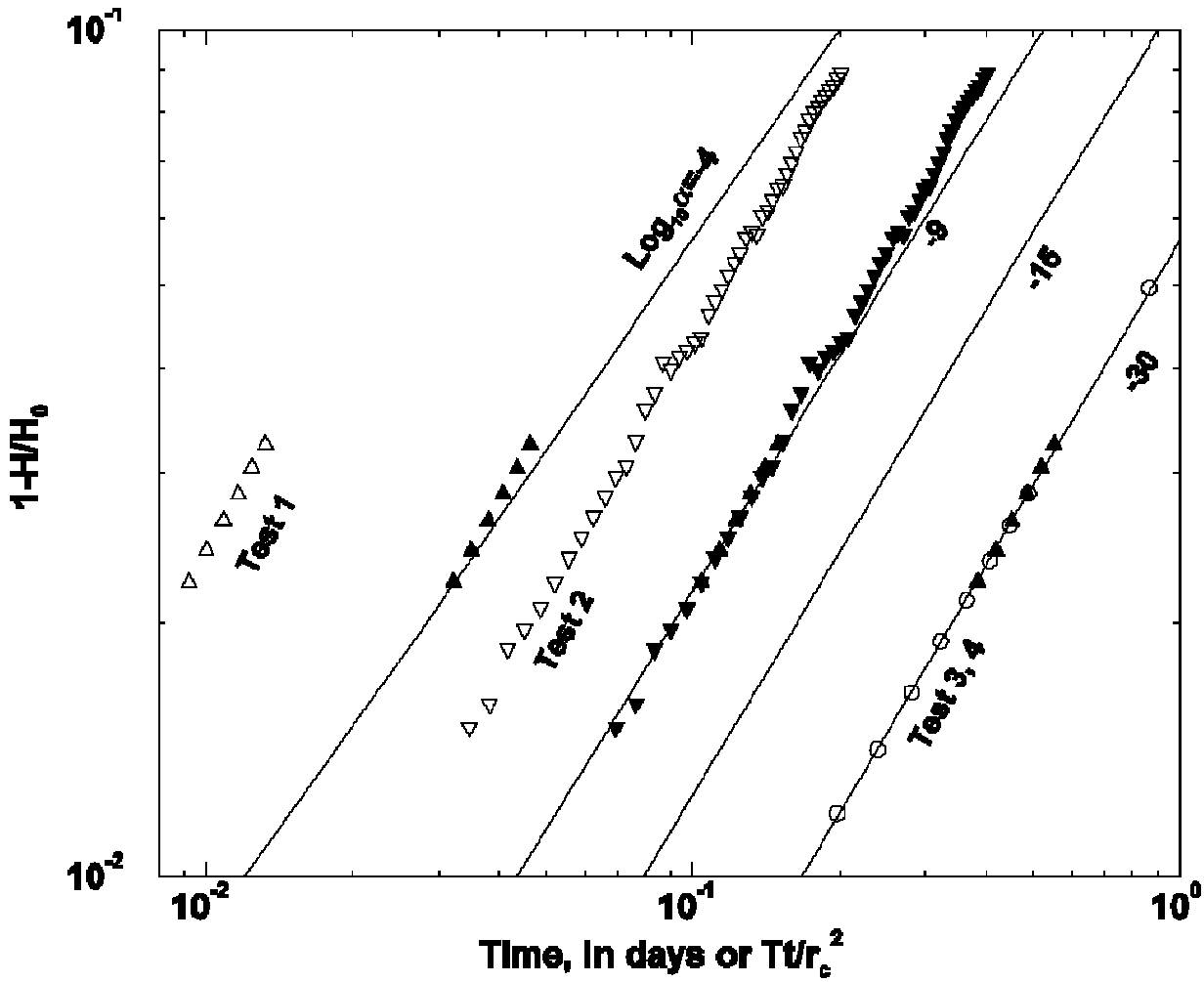

Figure 2. A. Data plots (labeled, open symbols) at an expanded scale for real time in days and as matched (filled symbols) to selected type curves. Type curves generated using Fortran program of Greene and Shapiro (1995).

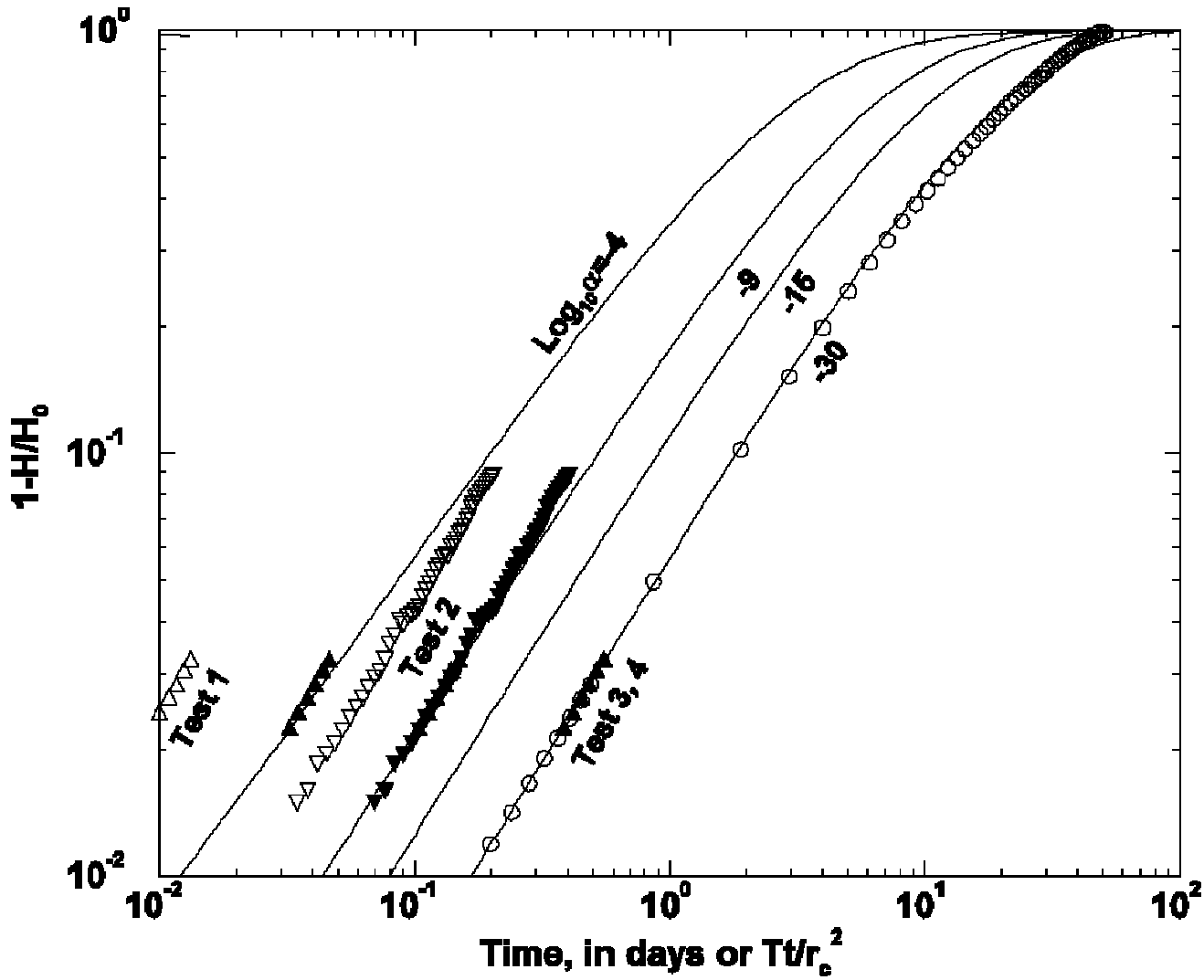

Figure 2. B. Same as Figure 1A, but showing the type curves to include complete recovery.

The $\alpha*$ value of 10^{-9} was chosen as the maximum value that matched the steepness of the data curve. The $\alpha*$ value that should be matched in the absence of well-bore clogging (s=0), $\alpha = \frac{r_w^2 S}{r_c^2}$, may be determined from well construction data and an estimate of S. Three well-controlled aquifer tests conducted on coal beds in the Powder River Basin provide a specific storage (S_s) for coals of about $6X10^{-6}$/ft (Weeks, 2005, p. 254). Assuming a similar S_s for the 48-ft thick (b) lignite bed at this site, $S=S_s b=3X10^{-4}$.

For this well, r_w= 3.5 in., and r_c=1.125 in. Thus, in the absence of clogging or well skin, α=3X10^{-3}, and a match to the $\alpha*$=10^{-9} type curve indicates substantial clogging. As a plausibility check, the e^{-2s} value needed to reduce $\alpha*$ to 10^{-9} from 3X10^{-3} is 3.3X10^{-7}, resulting in s = 7.5. Assuming a 1-in. thick clogged zone, ln (r_{skin}/r_w) is 0.25, so K_s is about 0.03 times that of the formation. The indicated 30-fold decline in K due to mud invasion seems plausible.

The fact that the log-log plot of head recovery for test 1 is steeper than the type curve plots for larger $\alpha*$ values could be due to ongoing well development as water entering the well removes fine materials from the well bore wall. In that case, use of the $\alpha*$=10^{-9} type curve to analyze the test may over-estimate clogging, and the computed KD value may thus be too large. To obtain a probable minimum estimate for KD and K, the earliest data were also matched to the $\alpha*=10^{-4}$ curve, as that may be about the maximum $\alpha*$ that would still allow well development to occur. For this match, T=3.5r_c^2, or about 0.03 ft^2/d, providing a minimum K value of 0.6X10^{-3} ft/d or about 0.4 mD. A maximum estimate of T and K for this test is more difficult to estimate. A match of the data to the $\alpha*$=10^{-30} curve provides a K of 6X10^{-3} ft/d or 3.4 mD. A 1-in. clogged layer would have to be about 100 times less permeable than the formation, within the realm of possibility, but perhaps unlikely at this stage of well completion and development.

Events Leading to Test 2

Following the end of electric tape recovery measurements at 11:50, tremie pipe was added and the well was air-lift pumped from a depth of 600 feet until about 13:00, when the casing slipped through the clamp and fell about 35 feet down the hole. Presumably, based on the various initial depths of packer, tail section bottom, and gravel top, the bottom of the well casing was now resting on the gravel surface, with 7 feet of open hole above the casing bottom. The resulting well configuration is shown in Figure 1C. Two new sections of casing were installed over the tremie pipe to salvage the well. Following the well collapse, a water level depth of about 48 feet was measured in the casing.

Air-lift pumping in the salvaged well was resumed at 15:30, and water levels were lowered to 500 feet by 16:30. Water level recovery was monitored for several

minutes beginning at 16:45, but recovery was quite slow (about 0.2 ft/minute), with somewhat erratic behavior, possibly due to water running down the casing, so no attempt was made to analyze these data. Pumping resumed about 17:00, and the well was evacuated to a depth of 780 feet by 18:30. Pumping from that depth continued until 20:10. At that time, 3 sections of tremie pipe were added, and the pressure transducer was emplaced at the 780-foot depth to record recovery overnight, beginning at 21:00.

Test 2

The record of overnight water level recovery constitutes test 2. Water levels were recorded every 5 minutes, and were found to be rising, based on a regression analysis, at a fairly uniform rate of about 0.23 foot/minute until 01:05 on September 8. After that time, the pressure head demonstrated major oscillations, presumably due to a well cave-in. After these oscillations, the rate of water level rise dampened, and by 03:00, had stopped completely, with an indicated DTW of about 667 feet.

Data for the period 21:00 to 01:00 were chosen for slug test analysis. The initial water level, at 20:10, was computed to be 758.4 ft, rounded to 758 feet. For the assumed static water level of 6 feet, H_0 becomes 752 feet. Transducer data were converted to DTW as described above, and SWL subtracted to provide H/H_0 at 5-minute uintervals. Times were converted to days elapsed since 20:10.

Data for test 2 are shown as the open inverted triangles in Figure 2. The early data match (solid inverted triangles) the type curve for $\alpha=10^{-9}$ reasonably well, resulting in $KD=2.0r_c^2$, or $1.8X10^{-2}$ ft^2/d. Assuming that the aquifer thickness had been diminished by an amount equal to the 35-ft drop of casing in the well, the aquifer thickness is now 13 ft, resulting in $K=1.4X10^{-3}$ ft/d or 0.8 mD. This value is, considering uncertainties in the analysis, basically the same as that of $2X10^{-3}$ ft/d determined from the short recovery test of the full open-hole section. This result indicates that the main factor affecting the results of test 2 relative to test 1 was a diminution in the section of hole providing water to the well. Later data for this plot show a somewhat steeper slope than any of the type curves. This may occur because of minor spalling that resulted in some

well development prior to the hypothesized major spalling and cave-in occurring at about 01:05 on 09/08.

Events Leading to Test 3

Prior to the resumption of air-lift pumping on 09/08/04, it was noted that the well casing had risen about 1 foot overnight, probably at the time of the hypothesized well cave-in. Presumably, fine materials surged into the 7-foot open hole section surrounding the steel tail pipe at that time, creating substantial pressure on the bottom of the packer that lifted the well. The caved materials likely later settled on the gravel, effectively sealing the previous open-hole section from the bottom of the tail pipe, thus reducing the well section supplying water from the lignite to no more than the gravel-filled section of 6 feet.

Air-lift pumping was conducted from 09:30 to 11:00, lowering the water level from 667 feet to about 1000 feet. The transducer was installed at the 1020-foot depth from 11:16 until 13:00 to measure recovery. The water level recovered about 1.5 feet during this interval, indicating that severe clogging, probably associated with the well cave-in, had occurred. No attempt was made to analyze these data, but it was decided to circulate fresh water in an attempt to reduce clogging. While lowering tremie pipe through the casing to circulate, a plug was encountered at a depth of about 1077 feet, or about 190 feet above the bottom of the casing. The plug was washed out, with particles of lignite and of fine gravel being suspended in the return flow. Flushing was continued until the tremie pipe had reached the gravel installed during well completion. Circulation was continued at that depth for about an hour to clean out the remaining open hole. However, fine materials may have sifted into the gravel, clogging the surficial gravel now surrounding the bottom of the casing.

Test 3

Following flushing of the well, air-lift development, taking the water level down to 300 feet in two stages, starting about 19:00 on September 8. Air lift was halted at 20:15, and the pressure transducer installed to monitor water levels overnight. The transducer was

programed to read pressure head at 5-minute intervals starting at 21:00, and was retrieved at 08:00 on September 9. These overnight readings were used to develop test 3. DTW, as measured with the electric tape, was 302.75 feet at 20:19:45. Assuming a DTW at 20:15 of 303 ft, and subtracting the 6-foot assumed SWL, H_0 = 297 feet. The initial transducer reading at 21:00 translated to a depth to water of 302.2 feet, for a column length of 295.2 feet. Times were converted to days elapsed since 20:15, and H/H_0 computed for hourly readings extracted from the record.

Results for test 3 are shown as the open circles in figure 2A, which fall on the $\alpha*=10^{-30}$ type curve, providing KD ($=r_c^2$) of $9X10^{-3}$ ft^2/d. For this match, the thickness to provide a K of 0.0015 ft/d d or 0.8 mD is 6 ft. This is equal to the thickness of the gravel layer, which would be consistent with the isolation of the well in the gravel by creation of a low-permeability layer at the gravel surface. Plausbility of the indicated well skin is difficult to assess, as the geometry of the bottom of the well casing resting in possibly clogged gravel does not fit the model of a radial annular clogged layer assumed in the development of slug test theory. Nonetheless, it seems reasonable that the effect of the low-permeability layer extending into the top of the gravel might mimic that of a clogged annular layer. Although the results of test 3 (and 4) are not inconsistent with those for tests1 1 and 2, the agreement may be fortuitous, and should be considered inconclusive.

Winter Data

Following removal of the transducer to obtain data for test 3, preparations were made to collect pressure head data from the well during the winter months of 2004-2005. The remaining annular space around the well casing, voided when the casing sank down the bore hole, was back-filled with bentonite grout and with drill cuttings. Two 10 W/m heat tapes, one 270 ft and the other 350 ft in length, were installed to allow ice that would freeze in the well above the permafrost depth to be melted. Recovery data were recorded over the winter, starting with installation of the transducer at 17:00 on September 9, 2004 and ending with its retrieval at 16:55 on May 7, 2005. The transducer was installed at a depth of 610 feet, and had been recording a barometric

pressure of about 33.4 feet before it was installed.

Pressure head above land surface was determined from the transducer readings by subtracting 643 ft, the depth (rounded) of the transducer plus the barometric pressure, from the initial pressure transducer reading, in feet. The resulting hydrograph (Figure 3) shows very strange behavior. For about the first 50 days, pressure head follows the trend that would be expected for its recovery from the air-lift pumping that occurred on September 8. Beginning at 1:00 a.m. on October 30, the pressure head spiked up, rising more than 22 feet in seven hours, followed by a decline of about 17 feet in 3 hours. Pressure head rose slowly, with one minor excursion, until November 1, when another sharp rise occurred, raising the pressure head from about at land surface to a height of about 65 feet above land surface by November 11. Pressure head remained quite stable at that magnitude until 01:00 on February 28, when it began to rise rapidly, reaching a peak of about 360 feet above land surface on March 18. After that time pressure head fluctuated and declined slowly until April 27, when it began to decline rapidly. Pressure head had declined to a reading putting it about 35 feet above land surface on May 7, the date the transducer was retrieved. Retrieval involved powering the heat tapes, the longer one at 10:30, and the shorter one at 11:45. The pressure head declined rapidly once the ice column in the well partially thawed (between 13:00 and 14:00), dropping by 64 feet during that hour. The transducer was pulled up after 14:00, but became stuck at a level at which the pressure read about 250 feet for two hours, after which time it was retrieved. Upon retrieval, the transducer was reading a barometric pressure of about 23 feet of water, rather than the 33+ feet that it had read on installation. The transducer had been significantly over-ranged during the period of high pressure head, and may be significantly out of calibration.

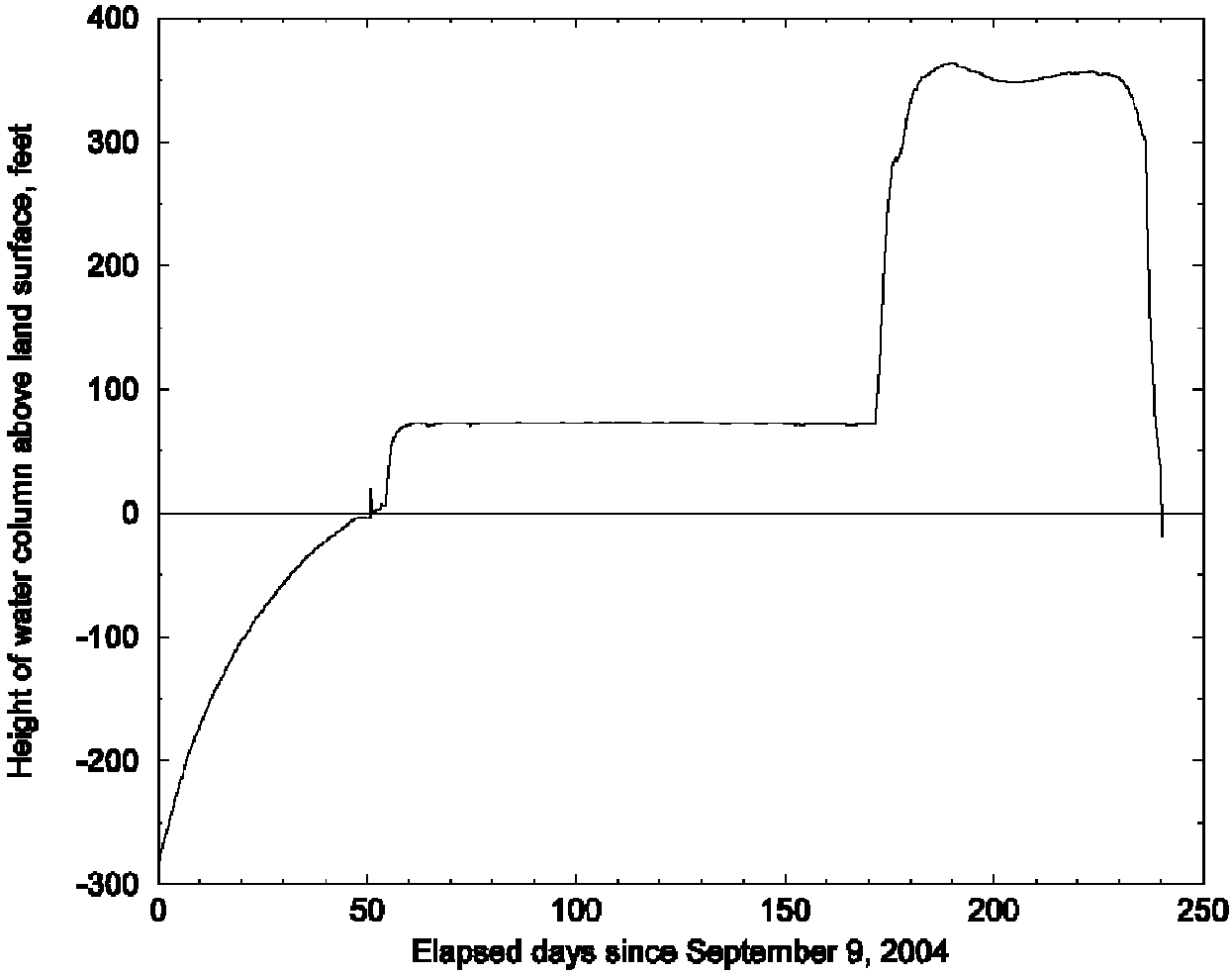

Figure 3. Graph of pressure head, in feet, vs. time for the Fort Yukon well, September 2004 to May 2005.

The pressure heads read by the transducer must represent a well phenomenon, indicating (possibly) that the bottom of the casing, sitting in the clogged gravel layer, became completely isolated from the coal aquifer at about the time that the water level fully recovered. The first pressure spike, on October 30, may have occurred as water froze over at some point in the well, sealing it from the surface. As the freezing front advanced downward, the expansion due to freezing may have pressurized the well, but this first ice seal may have fractured or slipped later that day. The well may have frozen over for good on November 1, with the freezing front again migrating downward to

stabilize after about 10 days. The rise beginning February 28 is more problematic. Possibly bacterial action began to generate gas that overpressured the ice-capped water column, with the well beginning to make some re-connection with the aquifer in early May. The pressure clearly was released completely when the ice in the well was thawed. The above are merely congectures, and the true cause of the strange well behavior may never be known. Nonetheless, it is extremely unlikely that the recorded pressure heads represent those in the formation.

Test 4 Analysis

Despite these problems, the early data, extending to October 30, appear to represent recovery from the air-lift pumping on September 8, and will be analyzed as such. Pressure head was computed as 638 ft (depth of 610 feet+ barometric pressure of 34 feet-6 ft SWL), minus the transducer reading. H_0 of 297 feet, the same as for test 3, is assumed. The resulting plot of $1-H/H_0$ vs. time is a continuation of the data plot for test 3, as it should be. The match points and determined KD and K values are the same for the two tests. After about 30 days and 80% recovery, the pressure head recovery is more rapid than predicted by slug-test theory. The cause of this is unknown, but has been observed by the authors for a few other slug tests on coal beds in the Powder River Basin of Montana and in central Alaska.

Summary and Conclusions

In summary, the testing regime for this well was fraught with difficulties and uncertainties. Development of the well was in progress when the casing slipped 35 feet, precluding an extensive test on the fully developed well open to 48 feet of lignite. Depressuring for the second test led to a cave-in of the well, further reducing its production capacity and effective KD. Despite these problems, the resultant slug tests provide a range of values that may bracket the true hydraulic conductivity or permeability of the coal. The results of matching the data for test 1 to a maximum probable $\alpha*$ value indicate a minimum hydraulic conductivity (permeability) of $6X10^{-4}$ ft/d (0.3 mD). The maximum hydraulic conductivity is less easily obtained. A 1-inch thick clogged layer that is 100 times less permeable than the lignite would result in a computed K of about $6X10^{-3}$ ft/d (3.3 mD). Such a permeability reduction is within the realm of possibility, but may overstate conditions for test 1. A good estimate of the permeability of the lignite at this site, based on reasonable agreement of K values for tests 1 and 2, may be about 0.8 mD. Consequently, coal-bed methane development would almost cetainly require hydraulic fracturing to enhance the lignite permeability, based on engineering criteria presented by Zuber (1996).

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