John Kieling, Acting Bureau Chief  
Hazardous Waste Bureau  
New Mexico Environment Department  
2905 Rodeo Park Drive East, Building 1  
Santa Fe, NM 87505-6303

Subject: Submittal of the Report for the Cross-Hole Pumping Test at R-66 and TW-3

Dear Mr. Kieling:

Enclosed please find two hard copies with electronic files of the Report for the Cross-Hole Pumping Test at R-66 and TW-3. The Laboratory is submitting this document as a separate, stand-alone report. Therefore, the Completion Report for Regional Well R-66 will not include an appendix on aquifer testing conducted at this well.

If you have any questions, please contact Ted Ball at (505) 665-3996 (tedball@lanl.gov) or Hai Shen at (505) 665-5046 (hai.shen@nnsa.doe.gov).

Sincerely,

Michael J. Graham, Associate Director  
Environmental Programs  
Los Alamos National Laboratory

Sincerely,

George J. Rael, Assistant Manager  
Environmental Projects Office  
Los Alamos Site Office
Enclosures: Two hard copies with electronic files – Report for the Cross-Hole Pumping Test at R-66 and TW-3 (LA-UR-12-0673)

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Report for the Cross-Hole Pumping Test at R-66 and TW-3
Los Alamos National Laboratory (LANL), operated by Los Alamos National Security (LANS), LLC, for the U.S. Department of Energy under Contract No. DE-AC52-06NA25396, has prepared this document to support the investigation and cleanup, including corrective action, of contamination at LANL, as required by the Compliance Order on Consent, signed March 1, 2005. The public may copy and use this document without charge, provided that this notice and any statement of authorship are reproduced on all copies.
Report for the
Cross-Hole Pumping Test at R-66 and TW-3

February 2012

Responsible project manager:

Ted Ball
Printed Name

Project Manager

Environmental Programs

Signature

Title

Organization

Date

2/24/12

Responsible LANS representative:

Michael J. Graham
Printed Name

Associate Director

Environmental Programs

Signature

Title

Organization

Date

2/27/12

Responsible DOE representative:

George J. Rael
Printed Name

Manager

DOE-LASO

Signature

Title

Organization

Date

2-29-2012
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1.0 INTRODUCTION

This report describes the hydraulic analysis of pumping tests conducted during January 2012 at R-66, a regional aquifer well located in Los Alamos Canyon near the confluence with DP Canyon in Technical Area 21 (TA-21) at Los Alamos National Laboratory (LANL or the Laboratory) (Figure 1.0-1). This report provides details regarding hydrologic tests conducted at the site that were proposed in the R-66 hydrologic testing work plan and approved by the New Mexico Environment Department (NMED) (LANL 2011, 206417; NMED 2011, 206498) to meet the requirements of NMED’s Approval with Modifications for the Drilling Work Plan for Regional Well R-66 (Test Well 3r) and email of clarification (Dale 2011, 206375; NMED 2011, 201630).

The tests on R-66 were conducted to characterize the saturated materials and quantify the hydraulic properties of the screened interval. An additional objective of the tests was to observe the hydraulic connection between R-66 and nearby regional wells TW-3 (approximately 240 ft away), R-6 (1700 ft away), and R-8 (3780 ft away). A final objective was to assess the effect of scaling on aquifer property determination. Most pumping tests conducted on the plateau are single-well tests, incorporating only the pumped well, whereas the R-66 test afforded the opportunity to monitor surrounding wells covering a broader area. An assessment was made comparing aquifer characteristic determination based on the pumped well only versus the multiple-well configuration. Testing consisted of brief trial pumping, a step-drawdown test, background water-level data collection, and a 96-h constant-rate pumping test.

As in most of the R-well pumping tests conducted on the Pajarito Plateau, an inflatable packer system was installed initially in R-66 to try to eliminate casing-storage effects and to obtain “snapshots” of valuable early drawdown and recovery data. The packer was used during the trial tests and the step-drawdown test. Then, the pump was pulled and rerun with the incorporation of a polyvinyl chloride (PVC) slave tube for transducer installation on a cable. This precluded use of the inflatable packer for the 96-h pumping test—not a limitation because early data response was already recorded during trial testing. Rerunning the transducer on a cable offered the advantage of observing extended pumping effects during the test and reprogramming the transducer as needed.

Use of the inflatable packer for the trial tests was effective at eliminating storage effects, thus allowing the use of early pumping and recovery data to accurately determine the formation properties in the vicinity of the well. Subsequent extended pumping using the slave tube allowed the flexibility of (1) observing drawdown response during the test in the event that strategic pumping rate adjustments would be required and (2) reprogramming the transducer with the recovery data collection protocol at any time once a decision on the length of the pumping test was determined.

As observed in several R-well pumping tests, the water produced from the well showed aeration. The quantity of air in the groundwater was not sufficient to degrade the pump performance. However, it may have caused gradual clogging/blockage of the pore spaces around the well bore, resulting in an artificial increase in drawdown over time, as described below.

In coordination with the pumping test effort, Los Alamos County shut down nearby municipal supply well O-4 at 4:52 p.m. on January 7, 2012, nearly 5 d before the 96-h test on R-66 began, to minimize the effect of operating O-4 on the extended test. This eliminated daily pumping cycles that would have been superimposed on the R-66 data but did result in a steady recovery trend throughout the test period, as discussed below.
1.1 Conceptual Hydrogeology

The R-66 screen is installed within Miocene riverine and fanglomerate deposits. The well screen is 20.3 ft long, extending from 819.4 to 839.7 ft below ground surface (bgs). The static water-level measured on January 8, 2012, was 792.8 ft bgs. The brass cap elevation at the well was surveyed at 6626.96 ft above mean sea level (amsl), making the water-level elevation 5834.16 ft amsl.

Because of the proximity of the water table to the top of the well screen (26.6 ft above it), unconfined aquifer conditions were assumed for R-66.

The total depth and saturated thickness of the riverine and fanglomerate deposits was not known. The borehole was originally advanced to a depth of 910.4 ft bgs (117.6 ft below the water table). There was no definition available of sediment properties—permeable zones versus aquitards—below that depth.

1.2 R-66 Testing

R-66 was tested from January 6 to 20, 2012. On January 6, a 5-horsepower (hp) pump was installed and operated long enough to fill the drop pipe and establish a suitable discharge rate. The 5-hp pump was used because initial reports had suggested that the well had only a low yield potential of around 2 gallons per minute (gpm).

Trial testing of R-66 began at 8:00 a.m. on January 7 at a discharge rate of 8.6 gpm and continued for 30 min. Following 30 min of recovery, a second trial test was performed at 9:00 a.m. for 30 min at a discharge rate of 8.55 gpm. Following shutdown, recovery data were recorded for 30 min, and a third trial test, a step-drawdown test, was conducted at several discharge rates 2.5, 4.75, 7.0, 9.3, and 11.3 gpm (the maximum rate of the 5-hp pump). This test was conducted for 150 min from 10:00 a.m. to 12:30 p.m.

Because of the greater than expected yield observed during the trial testing, when the pump was pulled to remove the inflatable packer and modify the string by adding a PVC slave tube, a larger, 10-hp pump was selected for the extended test. After running the 10-hp pump on January 9, brief pumping was performed on January 10 to fill the drop pipe and set a discharge rate.

Following more than 42 h of background data collection, the 96-h pumping test was begun at 8:00 a.m. on January 12, at an average discharge rate of 14.2 gpm. Pumping continued until 8:00 a.m. on January 16. Following shutdown, recovery data were recorded for 96 h until 8:00 a.m. on January 20, when the transducer was pulled from the well.

1.3 Aerated Groundwater

Consistent with observations in many of the recent R-well pumping tests, the presence of gas or air was detected in the groundwater during the R-66 pumping tests. It is possible the observed gas is natural. On the other hand, it is more likely that high-pressure compressed air used in the drilling process invaded the aquifer zones during drilling, collecting in the formation pore spaces and/or dissolving in the groundwater. When water is pumped from the aquifer, trapped gas or air in the formation pores can move with the pumped water as well as expand and contract in response to pressure changes. Also, pressure reduction associated with pumping can allow dissolved gas or air to come out of solution. The significant quantity of gas or air present in the formations in recently tested wells has had several effects, including (1) interfering with pump-operating efficiency, (2) causing transient changes in aquifer permeability, (3) inducing pressure transients as the gas or air expands and contracts, and (4) causing storage-like effects associated with changes in gas or air volume in the formation voids, filter pack, and/or well casing.
The presence of air/gas in the extended R-66 test may have had the effect of clogging aquifer pores around the well sufficiently to reduce the permeability of the sediments near the borehole. This was evidenced by a steady and disproportionate increase in drawdown inside the well greater than that associated with ordinary growth of the cone of depression, as discussed below.

Aerated water conditions (presence of numerous tiny bubbles) persisted during the trial tests, the step-drawdown test, and the first 2 d of the extended pumping test. During the final 2 d of the extended test, the water appeared clear and bubble-free.

2.0 BACKGROUND DATA

The background water-level data collected in conjunction with running the pumping tests allow the analyst to see what water-level fluctuations occur naturally in the aquifer and help distinguish between water-level changes caused by conducting the pumping test and changes associated with other causes.

Background water-level fluctuations have several causes, among them barometric pressure changes, operation of other wells in the aquifer, Earth tides, and long-term trends related to weather patterns. The background data hydrographs from the monitored wells were compared with barometric pressure data from the area to determine if a correlation existed.

Previous pumping tests on the plateau have demonstrated a barometric efficiency for most wells of between 90% and 100%. Barometric efficiency is defined as the ratio of water-level change divided by barometric pressure change, expressed as a percentage. In the initial pumping tests conducted on the early R-wells, downhole pressure was monitored using a vented pressure transducer. This equipment measures the difference between the total pressure applied to the transducer and the barometric pressure, with this difference being the true height of water above the transducer.

Subsequent pumping tests, including R-66, have utilized nonvented transducers. These devices simply record the total pressure on the transducer, that is, the sum of the water height plus the barometric pressure. This results in an attenuated “apparent” hydrograph in a barometrically efficient well. An example is a 90% barometrically efficient well. When monitored using a vented transducer, an increase in barometric pressure of 1 unit causes a decrease in recorded downhole pressure of 0.9 unit because the water level is forced downward 0.9 unit by the barometric pressure change. However, using a nonvented transducer, the total measured pressure increases by 0.1 unit (the combination of the barometric pressure increase and the water-level decrease). Thus, the resulting apparent hydrograph changes by a factor of 100 minus the barometric efficiency and in the same direction as the barometric pressure change, rather than in the opposite direction.

Barometric pressure data were obtained from the TA-54 tower site from the Waste and Environmental Services Division–Environmental Data and Analysis (WES-EDA) Group. The TA-54 measurement location is at an elevation of 6548 ft amsl, whereas the wellhead elevation is at 6625.86 ft amsl. The static water level in R-66 was 792.8 ft below land surface, making the water table elevation 5833.06 ft amsl. Therefore, the measured barometric pressure data from TA-54 had to be adjusted to reflect the pressure at the elevation of the water table within R-66.
The following formula was used to adjust the measured barometric pressure data:

\[
P_{WT} = P_{T5A4} \exp \left[ -\frac{g}{3.281R} \left( \frac{E_{R-66} - E_{T5A4}}{T_{T5A4}} + \frac{E_{WT} - E_{R-66}}{T_{WELL}} \right) \right]
\]

Equation 2.0-1

where

- \( P_{WT} \) = barometric pressure at the water table inside R-66
- \( P_{T5A4} \) = barometric pressure measured at TA-54
- \( g \) = acceleration of gravity, in m/sec\(^2\) (9.80665 m/sec\(^2\))
- \( R \) = gas constant, in J/Kg/degrees kelvin (287.04 J/Kg/K)
- \( E_{R-66} \) = land surface elevation at R-66 site, in feet (6625.86 ft)
- \( E_{T5A4} \) = elevation of barometric pressure measuring point at TA-54, in feet (6548 ft)
- \( E_{WT} \) = elevation of the water level in R-66, in feet (5833.06 ft)
- \( T_{T5A4} \) = air temperature near TA-54, in degrees kelvin (assigned a value of 31.6°F, or 272.9 K)
- \( T_{WELL} \) = air column temperature inside R-66, in degrees kelvin (assigned a value of 67.4°F, or 292.8 K)

This formula is an adaptation of an equation WES-EDA provided. It can be derived from the ideal gas law and standard physics principles. An inherent assumption in the derivation of the equation is that the air temperature between TA-54 and the well is temporally and spatially constant, and that the temperature of the air column in the well is similarly constant.

The corrected barometric pressure data reflecting pressure conditions at the water table were compared with the water-level hydrograph to discern the correlation between the two and to determine whether water-level corrections would be needed before data analysis.

3.0 IMPORTANCE OF EARLY DATA

When pumping or recovery first begins, the vertical extent of the cone of depression is limited to approximately the well screen length, the filter pack length, or the aquifer thickness in relatively thin permeable strata. For many pumping tests on the plateau, the early pumping period is the only time the effective height of the cone of depression is known with certainty because, soon after startup, the cone of depression expands vertically through permeable materials above and/or below the screened interval. Thus, the early data often offer the best opportunity to obtain hydraulic conductivity information because conductivity would equal the earliest-time transmissivity divided by the well screen length.

Unfortunately, in many pumping tests, casing-storage effects dominate the early-time data, potentially hindering the effort to determine the transmissivity of the screened interval. The duration of casing-storage effects can be estimated using the following equation (Schafer 1978, 098240).

\[
t_c = \frac{0.6(D^2 - d^2)}{Q/s}
\]

Equation 3.0-1

where

- \( t_c \) = duration of casing storage effect, in minutes
- \( D \) = inside diameter of well casing, in inches
\[ d = \text{outside diameter of column pipe, in inches} \]
\[ Q = \text{discharge rate, in gallons per minute} \]
\[ s = \text{drawdown observed in pumped well at time } t_c, \text{ in feet} \]

The calculated casing-storage time is quite conservative. Often, the data show that significant effects of casing storage have dissipated after about half the computed time.

For wells screened across the water table or wells in which the filter pack can drain during pumping, there can be an additional storage contribution from the filter pack. The following equation provides an estimate of the storage duration accounting for both casing and filter pack storage.

\[
t_c = \frac{0.6 \left[ (D^2 - d^2) + S_y \left( D_B^2 - D_C^2 \right) \right]}{Q/s}
\]

Equation 3.0-2

where \( S_y \) = short-term specific yield of filter media (typically 0.2)
\( D_B \) = diameter of borehole, in inches
\( D_C \) = outside diameter of well casing, in inches

This equation was derived from Equation 3.0-1 on a proportional basis by increasing the computed time in direct proportion to the additional volume of water expected to drain from the filter pack. (To prove this, note that the left-hand term within the brackets is directly proportional to the annular area [and volume] between the casing and drop pipe while the right-hand term is proportional to the area [and volume] between the borehole and the casing, which is corrected for the drainable porosity of the filter pack. Thus, the summed term within the brackets accounts for all of the volume [casing water and drained filter pack water] appropriately.)

In some instances, it is possible to eliminate casing-storage effects by setting an inflatable packer above the tested screen interval before conducting the test. As described previously, this approach was successful in the trial testing performed on R-66.

### 4.0 TIME-DRAWDOWN METHODS

Time-drawdown data can be analyzed using a variety of methods. Among them is the Theis method (1934-1935, 098241). The Theis equation describes drawdown around a well as follows:

\[
s = \frac{114.6Q}{T} W(u)
\]

Equation 4.0-1

where

\[
W(u) = \int_u^\infty \frac{e^{-x}}{x} dx
\]

Equation 4.0-2
and

\[ u = \frac{1.87r^2S}{Tt} \]  

\textbf{Equation 4.0-3}

and where  
\( s \) = drawdown, in feet  
\( Q \) = discharge rate, in gallons per minute  
\( T \) = transmissivity, in gallons per day per foot  
\( S \) = storage coefficient (dimensionless)  
\( t \) = pumping time, in days  
\( r \) = distance from center of pumpage, in feet

To use the Theis method of analysis, the time-drawdown data are plotted on log-log graph paper. Then, Theis curve matching is performed using the Theis type curve—a plot of the Theis well function \( W(u) \) versus \( 1/u \). Curve matching is accomplished by overlaying the type curve on the data plot and, while keeping the coordinate axes of the two plots parallel, shifting the data plot to align with the type curve, effecting a matched position. An arbitrary point, referred to as the match point, is selected from the overlapping parts of the plots. Match-point coordinates are recorded from the two graphs, yielding four values: \( W(u), 1/u, s, \text{ and } t \). Using these match-point values, transmissivity and storage coefficient are computed as follows:

\[ T = \frac{114.6Q}{s}W(u) \]  

\textbf{Equation 4.0-4}

\[ S = \frac{Tut}{2693r^2} \]  

\textbf{Equation 4.0-5}

where  
\( T \) = transmissivity, in gallons per day per foot  
\( S \) = storage coefficient  
\( Q \) = discharge rate, in gallons per minute  
\( W(u) \) = match-point value  
\( s \) = match-point value, in feet  
\( u \) = match-point value  
\( t \) = match-point value, in minutes

An alternate solution method applicable to time-drawdown data is the Cooper-Jacob method (1946, 098236), a simplification of the Theis equation that is mathematically equivalent to the Theis equation for most pumped well data. The Cooper-Jacob equation describes drawdown around a pumping well as follows:

\[ s = \frac{264Q}{T}\log\frac{0.3Tt}{r^2S} \]  

\textbf{Equation 4.0-6}
The Cooper-Jacob equation is a simplified approximation of the Theis equation and is valid whenever the u value is less than about 0.05. For small radius values (e.g., corresponding to borehole radii), u is less than 0.05 at very early pumping times and therefore is less than 0.05 for most or all measured drawdown values. Thus, for the pumped well, the Cooper-Jacob equation usually can be considered a valid approximation of the Theis equation. An exception occurs when the transmissivity of the aquifer is very low. In that case, some of the early pumped well drawdown data may not be well approximated by the Cooper-Jacob equation.

According to the Cooper-Jacob method, the time-drawdown data are plotted on a semilog graph, with time plotted on the logarithmic scale. Then a straight line of best fit is constructed through the data points and transmissivity is calculated using the following:

\[ T = \frac{264Q}{\Delta s} \]  

Equation 4.0-7

where  
\( T \) = transmissivity, in gallons per day per foot  
\( Q \) = discharge rate, in gallons per minute  
\( \Delta s \) = change in head over one log cycle of the graph, in feet

Because many of the test wells completed on the plateau are severely partially penetrating, an alternate solution considered for assessing aquifer conditions is the Hantush equation for partially penetrating wells (Hantush 1961, 098237; Hantush 1961, 106003). The Hantush equation is as follows:

\[ s = \frac{Q}{4\pi T} \left[ W(u) + \frac{2b^2}{\pi^2(l-d)(l'-d')} \sum_{n=1}^{\infty} \frac{1}{n^2} \left( \sin \frac{n\pi d}{b} - \sin \frac{n\pi l}{b} \right) \left( \sin \frac{n\pi d'}{b} - \sin \frac{n\pi l'}{b} \right) W\left(u, \sqrt{\frac{K_z}{K_r}} \frac{n\pi r}{b} \right) \right] \]

where, in consistent units, \( s, Q, T, t, r, S, \) and \( u \) are as previously defined and  
\( b \) = aquifer thickness  
\( d \) = distance from top of aquifer to top of well screen in pumped well  
\( l \) = distance from top of aquifer to bottom of well screen in pumped well  
\( d' \) = distance from top of aquifer to top of well screen in observation well  
\( l' \) = distance from top of aquifer to bottom of well screen in observation well  
\( K_z \) = vertical hydraulic conductivity  
\( K_r \) = horizontal hydraulic conductivity

In this equation, \( W(u) \) is the Theis well function and \( W(u,\beta) \) is the Hantush well function for leaky aquifers where

\[ \beta = \sqrt{\frac{K_z}{K_r}} \frac{n\pi r}{b} \]  

Equation 4.0-9

Note that for single-well tests, \( d = d' \) and \( l = l' \).
5.0 RECOVERY METHODS

Recovery data were analyzed using the Theis recovery method. This is a semilog analysis method similar to the Cooper-Jacob procedure.

In this method, residual drawdown is plotted on a semilog graph versus the ratio \( t/t' \), where \( t \) is the time since pumping began, and \( t' \) is the time since pumping stopped. A straight line of best fit is constructed through the data points, and \( T \) is calculated from the slope of the line as follows:

\[
T = \frac{264Q}{\Delta s}
\]

Equation 5.0-1

The recovery data are particularly useful compared to time-drawdown data. Because the pump is not running, spurious data responses associated with dynamic discharge rate fluctuations are eliminated. The result is that the data set is generally “smoother” and easier to analyze.

Recovery data also can be analyzed using the Hantush equation for partial penetration. This approach is generally applied to the early data in a plot of recovery versus recovery time.

6.0 SPECIFIC CAPACITY METHOD

The specific capacity of the pumped well can be used to obtain a lower-bound value of hydraulic conductivity. The hydraulic conductivity is computed using formulas that are based on the assumption that the pumped well is 100% efficient. The resulting hydraulic conductivity is the value required to sustain the observed specific capacity. If the actual well is less than 100% efficient, it follows that the actual hydraulic conductivity would have to be greater than calculated to compensate for well inefficiency. Thus, because the efficiency is unknown, the computed hydraulic conductivity value represents a lower bound. The actual conductivity is known to be greater than or equal to the computed value.

For fully penetrating wells, the Cooper-Jacob equation can be iterated to solve for the lower-bound hydraulic conductivity. However, the Cooper-Jacob equation (assuming full penetration) ignores the contribution to well yield from permeable sediments above and below the screened interval. To account for this contribution, it is necessary to use a computation algorithm that includes the effects of partial penetration. One such approach was introduced by Brons and Marting (1961, 098235) and augmented by Bradbury and Rothschild (1985, 098234).

Brons and Marting introduced a dimensionless drawdown correction factor, \( s_P \), approximated by Bradbury and Rothschild as follows:

\[
s_P = \left[ 1 - \frac{L}{b} \ln \left( \frac{b}{r_w} \right) - 2.948 + 7.363 \left( \frac{L}{b} \right) - 11.447 \left( \frac{L}{b} \right)^2 + 4.675 \left( \frac{L}{b} \right)^3 \right]
\]

Equation 6.0-1

In this equation, \( L \) is the well screen length, in ft. Incorporating the dimensionless drawdown parameter, the conductivity is obtained by iterating the following formula:

\[
K = \frac{264Q}{sb} \left( \log \frac{0.3Tt}{r_w^2S} + \frac{2s_P}{\ln 10} \right)
\]

Equation 6.0-2
The Brons and Marting procedure can be applied to both partially penetrating and fully penetrating wells. To apply this procedure, a storage coefficient value must be assigned. Storage coefficient values generally range from $10^{-5}$ to $10^{-3}$ for confined aquifers and 0.01 to 0.25 for unconfined aquifers (Driscoll 1986, 104226). For R-66, unconfined conditions were assumed, so calculations were performed for an arbitrarily assigned storage coefficient of 0.10. The lower-bound transmissivity calculation result is not particularly sensitive to the choice of storage coefficient value, so a rough estimate is generally adequate to support the calculations.

The analysis also requires assigning a value for the saturated aquifer thickness, $b$. For R-66, calculations were performed for an arbitrarily assigned aquifer thickness of 100 ft. For partially penetrating conditions, the calculations are not particularly sensitive to the choice of aquifer thickness because sediments far above or below the screen typically contribute little flow.

7.0 BACKGROUND DATA ANALYSIS

Background aquifer pressure data collected during the R-66 tests were plotted along with barometric pressure to determine the barometric effect on water levels.

Figure 7.0-1 shows aquifer pressure data from R-66 during the test period along with barometric pressure data from TA-54 that have been corrected to equivalent barometric pressure in feet of water at the water table. The R-66 data are referred to in the figure as the “apparent hydrograph” because the measurements reflect the sum of water pressure and barometric pressure, having been recorded using a nonvented pressure transducer. The time of the extended pumping test period for R-66 is included in the figure for reference.

A comparison of the apparent hydrograph and barometric pressure curve showed little correlation between the two, suggesting a high barometric efficiency for R-66, likely close to 100%.

The primary trend illustrated in the figure was a daily sinusoidal pressure response in the recovery data. It was likely that this reflected a response to pumping municipal well PM-3. The pumping times for PM-3 operation for this time period are shown in the figure. The declines in R-66 water levels match the pumping cycles for PM-3, although with a slight delay that is reasonable given the long distance to PM-3 (about 1.2 mi). Alternatively, as explained below, the water-level cycles in R-66 may have been a response to water-level changes in nearby production well O-4, which, in turn, were caused by the operation of PM-3. If this were the mechanism indirectly affecting water levels in R-66, the time delay in the response would be explained by relatively slow propagation of the effect through the unconfined upper portion of the regional aquifer.

Figure 7.0-2 shows data recorded in well TW-3, located 240 ft from R-66. The barometric pressure curve and the time of the extended pumping period for R-66 are shown on the graphs for reference. Because a vented transducer was used to measure the TW-3 water levels, and the barometric pressure fluctuations in the hydrograph were large, it was necessary to correct the water-level data by removing the barometric effect. This was done using BETCO (barometric and Earth tide correction) software—a mathematically complex correction algorithm that uses regression deconvolution (Toll and Rasmussen 2007, 104799) to modify the data by accounting for current and antecedent barometric pressure effects.

The drawdown and recovery associated with pumping R-66 are evident on the BETCO-corrected hydrograph. However, the data pattern lacked the symmetry normally observed in pumping test response curves in that the drawdown trend appeared to level off while the recovery trend remained steep, showing
a recovered level higher than the starting level. This pattern was attributed to ongoing water-level rebound associated with the antecedent shutdown of nearby well O-4. Overall, the apparent rise in water level between the start of pumping on January 12 and the conclusion of the recovery period on January 20 averaged 0.031 ft/d.

As a first-cut approximation, the estimated water-level rebound was assumed to be linear (at 0.031 ft/d), and the BETCO-corrected data were corrected further for this trend. The resulting plot is shown in Figure 7.0-3. This plot suggests a drawdown of about 0.3 ft after 4 d of pumping, followed by 0.3 ft of recovery 4 d later. This corrected plot was assumed to reasonably approximate the drawdown and recovery response to the extended pumping test on R-66.

Figure 7.0-4 shows water levels measured in well O-4 from January 15 to 21. The daily cycles shown on the graph are a response to PM-3 operation. The relatively large magnitude of the fluctuations results from the hydraulic connection between O-4 and PM-3 through the deep, confined, transmissive water supply aquifer. It is possible the daily water-level cycles observed in R-66 (Figure 7.0-1) might have been caused wholly, or in part, by the PM-3-induced changes in water levels in nearby well O-4 rather than directly from PM-3. The O-4 borehole likely serves as a conduit facilitating transmission of the PM-3 pressure wave from the deep aquifer to the shallow portion of the regional aquifer. This could explain why the PM-3 effect is seen in R-66 about 170 ft from well O-4 but is not evident in TW-3 (Figures 7.0-2 and 7.0-3), which is located over 400 ft from O-4.

Data were collected from R-6 and R-8 during the R-66 pumping tests. Neither of these wells responded to R-66 operation, and the data collected are not included in this report.

8.0 WELL R-66 DATA ANALYSIS

This section presents the data obtained from the R-66 pumping tests and the results of the analytical interpretations. Data are presented for trial 1, trial 2, the step-drawdown test, and the 96-h constant-rate test.

8.1 Well R-66 Trial 1 Test

Brief trial testing was performed to obtain “snapshots” of early pumping and recovery response to try to quantify properties of the subsurface materials immediately around the wellbore. Figure 8.1-1 shows a semilog plot of the drawdown data collected from the trial 1 test on R-66 at a discharge rate of 8.6 gpm. The early data show exaggerated drawdown briefly (half a minute), caused by an elevated pumping rate associated with refilling the drop pipe.

Cold weather conditions required draining a portion of the drop pipe between pumping events to prevent freezing. On initial startup, the backpressure on the pump was low temporarily, and the corresponding discharge was elevated, until the drop pipe and discharge pipe ahead of the flow control valve were filled. Once the discharge piping was filled, the presence of the partially closed valve increased the effective operating head, reducing the discharge rate accordingly.

The transmissivity computed from the line of fit shown on the graph was 1330 gallons per day (gpd)/ft. Because half a minute had already elapsed, it was suspected that the cone of depression had already expanded vertically and that this transmissivity represented some unknown sediment thickness greater than the well screen length. Later data showed continuing flattening of the drawdown graph, consistent with partial penetration effects/vertical growth of the cone of depression.
Figure 8.1-2 shows a semilog plot of the recovery data collected from the trial 1 test on R-66 following pump shutoff. Very early data, free from pumping rate variations, were obtained from the recovery response. The initial slope shown on the plot revealed a transmissivity of 860 gpd/ft for the screened interval. Based on the well screen length of 20.3 ft, the computed hydraulic conductivity was 42 gpd/ft², or 5.7 ft/d.

The subsequent slope produced a transmissivity value of 1340 gpd/ft, consistent with that obtained from the time-drawdown graph. This represents the transmissivity of an unknown thickness of sediments greater than the screened interval.

Late recovery data showed continued flattening associated with vertical growth of the cone of impression.

8.2 Well R-66 Trial 2 Test

Figure 8.2-1 shows a semilog plot of the drawdown data collected from the trial 2 test on R-66 at a discharge rate of 8.55 gpm. As with trial 1, the early data showed the effects of a brief elevated pumping rate associated with antecedent drainage of the upper portion of the discharge piping to prevent freezing. The transmissivity determined from the plot was 1240 gpd/ft, representing an unknown interval of sediment greater than the screen length. The late data showed continued flattening of the drawdown curve, consistent with vertical growth of the cone of depression.

Figure 8.2-2 shows a semilog plot of the recovery data collected from the trial 2 test on R-66. The very early data supported a transmissivity calculation of 890 gpd/ft for the screened interval, resulting in a computed hydraulic conductivity of 44 gpd/ft, or 5.9 ft/d. The subsequent slope showed a transmissivity of 1300 gpd/ft, corresponding to an unknown thickness of sediment greater than the screened interval. Finally, the late recovery data showed the same flattening effect associated with vertical growth of the cone of depression.

8.3 Well R-66 Step-Drawdown Test

A third trial test, a step-drawdown test, was conducted to evaluate pumping response at several discharge rates and support selection of a suitable pumping rate for the extended test. The test included five pumping steps of 30 min duration at successive discharge rates of 2.5, 4.75, 7.0, 9.3, and 11.3 gpm. The final rate of 11.3 gpm was the maximum capacity of the 5-hp pump that had been installed for the trial and step-drawdown testing.

Figure 8.3-1 shows the drawdown measured during the step-drawdown test. The specific capacities calculated for the five steps were, successively, 1.24, 1.19, 1.13, 1.07, and 0.92 gpm/ft. As this list shows, during the first four steps there was a slight decline in specific capacity of about 0.06 gpm/ft per step with increasing pumping rates, suggesting the possibility of minor turbulent flow with the higher pumping rates. However, while drawdown data from the first three steps appeared to be leveling off, data from the fourth step showed an inflection point and a slight increase in slope near the end of the step. Then, during the final (fifth) step, there was a disproportionate reduction in specific capacity and an even more prominent indication of an inflection point and curve steepening at late time.

The observed response of water levels stabilizing initially and then declining disproportionately later on indicated that a dynamic deterioration in well efficiency was occurring during the test. It was possible that this was an indication of air bubbles forming in the sediment pore spaces during the test. Accumulation of air or gas in formation pores has the effect of reducing the hydraulic conductivity of the sediment and degrading the specific capacity of the well.
Based on the observed specific capacity values during the step-drawdown test, R-66 appeared capable of producing on the order of 20 gpm. However, because of the indication of transient efficiency reduction during brief testing, it was presumed that the discharge rate would have to be constrained to less than this to avoid the risk of dewatering a substantial portion of the well screen during the extended test. Ultimately, the decision was made to restrict the pumping rate to around 14 gpm for the 96-h pumping test. As discussed below, the extended test was run at an average discharge rate of 14.2 gpm. At this pumping rate, dewatering of the well screen was avoided for the first 3 d of pumping. During the final day of the extended test, the pumping level dropped into the screen about a foot.

8.4 Well R-66 96-h Constant-Rate Test

Figure 8.4-1 shows a semilog plot of the drawdown data collected from the 96-h constant-rate pumping test conducted at an average discharge rate of 14.2 gpm. Casing storage times are shown on the graph for reference. The substantial casing-storage effect was a result of not using an inflatable packer.

As shown on the graph, after 5 min of pumping the flow control valve malfunctioned, resulting in a sudden reduction in discharge rate. The valve was readjusted to restore the initial pumping rate.

During the first hour or so of pumping, the drawdown slope gradually flattened. This meant that the flattening effect associated with vertical growth of the cone of depression kept pace with any well efficiency deterioration that was occurring. After an hour, however, there was a steady increase in the drawdown slope, and this persisted throughout the remainder of the pumping test. This may have been caused by continued accumulation of gas/air in the formation pores and concomitant reduction in well efficiency.

As shown on the graph, after about 3 d of pumping the water level reached the top of the well screen. Gradually, the water level dropped about a foot into the screen by the end of the test.

As shown on the graph, the drawdown data trace appeared “lumpy,” showing a daily sinusoidal pattern with an amplitude of a fraction of a foot. This effect was from a cyclical change in discharge rate caused by daily variations in the electrical supply output hertz. When the ambient air temperature dropped overnight, the power supply hertz increased, speeding up the pump slightly and increasing the flow rate. During the day, as the ambient air temperature increased, the electrical output frequency decreased slightly and caused a reduction in flow rate.

Figure 8.4-2 shows an expanded-scale plot of the early drawdown data from the extended test. The transmissivity determined from the line of fit shown on the figure was 1400 gpd/ft, in agreement with values obtained from the trials 1 and 2 drawdown graphs. This transmissivity likely represents an unknown thickness of sediment greater than the well screen length.

Figure 8.4-3 shows the recovery data collected following shutdown of the 96-h constant-rate pumping test. As shown in the figure, nearly all of the recovery distance corresponded to casing-storage effects. The rapid recovery likely was an indication of hysteretic effects. In unconfined aquifers, the early rate of recovery can be more rapid than that of drawdown because of a smaller effective storage coefficient during recovery. During pumping the capillary fringe above the water table increases in thickness, while during recover it gets thinner (Bevan et al. 2005, 105186). If the rate of thinning during recovery exceeds the rate of growth during pumping, the effective storage coefficient during recovery will be less than that during pumping, resulting in a more rapid initial recovery rate than drawdown rate, followed by a corresponding slowing of the recovery rate at late time. Additionally, as the water table rebounds during recovery, it can trap air in the previously dewatered pore spaces, further decreasing the effective recovery storage coefficient. It was also possible that extraneous air already in the formation, or air that was
dissolved in the groundwater and came out of solution during pumping, contributed to a reduced storage coefficient initially and then a greater storage coefficient as rising water levels compressed the air bubbles. Because of these probable effects, the recovery data were not analyzable.

Figure 8.4-4 shows an expanded-scale plot of the recovery data. This plot confirms the rapid initial recovery and subsequent flat slope attributable to hysteretic effects. Note that the theoretical storage times shown on the plot, which were computed based on casing volume, appeared to underestimate the actual storage effect duration. It was possible that the accumulated air bubbles in the formation pores, which would have compressed during recovery, might have added to the effective storage volume. Also, compression of air that entered the filter pack behind the blank casing above the well screen, when the top of the screen was dewatered, would have contributed to an increased storage effect.

The daily “ripples” apparent on the expanded-scale plot show the effects of PM-3 operation. Finally, the overall recovery trend was slight—averaging just a few hundredths of a foot per day. It was likely that this was ongoing water-level rebound associated with shutting down municipal production well O-4 rather than actual aquifer water-level recovery. This implied that hysteretic effects had resulted in essentially complete recovery of R-66 water levels within about a half hour or so of pump shutoff. (Note that the recovery data were not corrected for water-level rebound.)

Figure 8.4-5 shows a plot comparing the drawdown and recovery data sets. In theory, these plots should nearly coincide. In fact, they diverge substantially, confirming the occurrence of a steady well efficiency decline during the pumping portion of the test. Again, the most likely explanation of this effect was accumulation of air in the formation pores during the pumping test.

The modified hydrograph data from TW-3 shown in Figure 7.0-3 were used to develop estimated drawdown and recovery plots. Figure 8.4-6 shows the resulting time-drawdown data plot. The analysis of the data showed an estimated transmissivity of 24,000 gpd/ft. This can be considered a rough approximation of the bulk transmissivity of the hydraulically contiguous zone penetrated by R-66. There was no way to know the corresponding thickness of the interval having this transmissivity. The storage coefficient calculated from the analysis was 0.0042, less than expected from an unconfined aquifer. This was as it should be because the storage coefficient calculation is based on fully penetrating conditions. The actual situation, with partially penetrating screens in R-66 and TW-3 that are nearly overlapping, results in exaggerated drawdown in TW-3 compared with what would have been observed in a fully penetrating observation well. The exaggerated drawdown results in a reduced storage coefficient value when applying standard formulas. Because of the long distance between R-66 and TW-3, persistence of partial penetration effects as far away as TW-3 suggested the possibility of severe vertical anisotropy for the hydraulically contiguous sediments.

Figure 8.4-7 shows the recovery data from TW-3, plotted as calculated recovery versus time since pumping stopped. The calculated recovery was determined by extrapolating the original drawdown trend and computing the difference between the extrapolated drawdown and the observed residual drawdown. This type of plot tends to provide independent corroboration of formation properties from the early data. The late data, however, tend to simply reflect the properties already estimated from the time-drawdown analysis. The transmissivity computed from the plot was 27,000 gpd/ft. Again, there was no way to know what thickness of hydraulically contiguous sediment corresponded to this value. The storage coefficient computed from the analysis was 0.0019, smaller than a typical unconfined value as expected because of partial penetration effects.

The data from TW-3 were analyzed using the Hantush method so that partial penetration and vertical anisotropy could be included in the calculations. To apply the Hantush method, it is necessary to assign an aquifer thickness and a vertical anisotropy ratio. In the absence of geologic data supporting an
understanding of the effective aquifer thickness, a range of arbitrary thicknesses was used in the analysis from 150 ft to 400 ft. Analyses were performed for anisotropy ratios ranging from 0.001 (severely anisotropic) to 1.0 (isotropic). For each combination of thickness and anisotropy, curve matching was used to compute the hydraulic conductivity.

Figure 8.4-8 shows the resulting hydraulic conductivity values as a function of anisotropy for aquifer thicknesses of 150, 200, 300, and 400 ft. The gaps in each of the curves correspond to anisotropy values for which poor-fitting curve matches were observed, while the graphed portions denote anisotropy values for which relatively good matches were obtained.

The computed hydraulic conductivity ranged from less than 10 to more than 40 ft/d, depending on the input assumptions. Thus, it was not possible to constrain the computed large-scale aquifer properties accurately within a narrow range using this analysis. There were two reasons for this: (1) there was no geologic identification of underlying aquitards to guide selection of an appropriate aquifer thickness and (2) accurate determination of unique hydraulic conductivity and vertical anisotropy values simultaneously generally requires the availability of observation wells spanning a large vertical section of the aquifer (Schafer 1998, 211226), whereas both the pumped well and observation well in this case were screened near the top of the aquifer.

8.5 Well R-66 Specific Capacity Data

Specific capacity data were used along with well geometry to estimate a lower-bound hydraulic conductivity value for the permeable zone penetrated by R-66. This was done to provide a frame of reference for evaluating the foregoing analyses.

Early pumping data were used to estimate the specific capacity because late data were biased by inefficiency associated with air buildup in the formation. Data from trial 1 were selected for the analysis. In trial 1, R-66 produced 8.6 gpm with 7.94 ft of drawdown after 30 min of operation for a short-term specific capacity of 1.08 gpm/ft.

In addition to specific capacity and pumping time, other input values used in the calculations included an assigned storage coefficient of 0.1, a borehole radius of 0.47 ft (inferred from the volume of filter pack required to backfill the screened zone), and an arbitrary saturated thickness of 100 ft.

Applying the Brons and Marting method to these inputs yielded a lower-bound hydraulic conductivity estimate for the screened interval of 42.7 gpd/ft², or 5.7 ft/d. This was consistent with values obtained from analysis of early recovery data from the trial tests.

9.0 COMPARISON OF PUMPED WELL VERSUS OBSERVATION WELL ANALYSES

Data from the pumped well and observation well supplied somewhat different information. For example, drawdown and recovery analyses from observation well TW-3 provided an approximation of the overall transmissivity of the hydraulically contiguous sediments stressed by pumping R-66. However, there was no way to know the corresponding aquifer thickness and, therefore, the average hydraulic conductivity. Likewise, using partial penetration analysis for assumed aquifer thickness values, the estimated hydraulic conductivity and transmissivity values were not unique, varying as a function of the assigned (unknown) value of vertical anisotropy. The pumped well data, on the other hand, supported an accurate determination of the hydraulic conductivity of the screened interval. Of note is that it was essential to implement an inflatable packer in the test apparatus to achieve this goal.
In some R-well pumping tests on the plateau, data from the pumped well have supported determination of the overall transmissivity of the hydraulically contiguous aquifer. In the R-66 test, however, this was not possible. The drawdown data were affected by dynamic well efficiency degradation during pumping, precluding effective use of the late-time response. Meanwhile, hysteretic effects negated the possible use of the recovery data for this.

10.0 SUMMARY

Constant-rate pumping tests were conducted on R-66 to gain an understanding of the hydraulic characteristics of the screened interval and investigate hydraulic interconnection to nearby wells.

A comparison of barometric pressure and R-66 water-level data showed a highly barometrically efficient screened zone. The primary background effect observed in R-66 was a daily drawdown and recovery of a few hundredths of a foot in response to operation of municipal production well PM-3.

Implementation of an inflatable packer was successful in obtaining early data "snapshots," which allowed determination of the hydraulic conductivity of the screened interval. The computed hydraulic conductivity value obtained from early recovery data averaged about 43 gpd/ft², or 5.7 ft/d.

During the 96-h pumping test, dynamic reduction in the hydraulic conductivity of the near-well sediments, as well as degradation of the specific capacity of the pumped well, occurred throughout the test, possibly from gas bubbles accumulating in the formation pores. This resulted in an exaggerated slope on the time-drawdown graph, which, therefore, did not support analysis. Anticipating this specific capacity reduction, the decision had been made to restrict the extended test rate to 14.2 gpm to avoid dewatering a significant portion of the well screen. The screen remained fully saturated for the first 3 d of the test, then dewatered about a foot during the fourth day of pumping.

Recovery data from the 96-h test showed hysteretic effects typical of unconfined aquifers and also exacerbated by accumulation of excess gas/air in the formation voids during pumping. The result was essentially complete water-level recovery within a half hour of pump shutoff, precluding analytical examination of the late recovery data.

Water-level data were collected from TW-3 (240 ft away from R-66), R-6 (1700 ft away) and R-8 (3780 ft away) during the R-66 test. Only well TW-3 showed a drawdown response to pumping R-66. During the test, the water level in TW-3 appeared to show a background rise of about 0.031 ft/d in response to antecedent shutdown of municipal well O-4 five days before the test. After correcting the TW-3 data for this background effect, the drawdown and recovery data supported a transmissivity estimate of about 25,000 gpd/ft for the hydraulically contiguous sediments affected by R-66 pumping. There was no way to know the thickness of the responding zone and, thus, it was not possible to compute an average hydraulic conductivity. Likewise, using partial penetration analysis for assumed aquifer thickness values, the estimated hydraulic conductivity and transmissivity were not unique, varying as a function of the assigned (unknown) value of vertical anisotropy.

One of the stated objectives of the R-66 pumping test was to determine whether large-scale aquifer properties could be computed more accurately using data from multiple wells than when relying solely on pumped well data. For the specific case of R-66, the pumped well data supported only a determination of the local-scale aquifer hydraulic conductivity near the screened interval. Determination of large-scale properties was precluded by dynamic changes in well efficiency (air clogging of the formation pores) during the pumping portion of the test and hysteretic effects during recovery. In theory, the time-drawdown and recovery data from a single well test can support determination of large-scale properties,
and this has been possible in other R-well pumping tests on the plateau. However, when dynamic efficiency variations and hysteretic effects occur, as they did in R-66, this is not possible. The observation well data provided the opportunity to estimate large-scale aquifer properties. However, the lack of geologic data on the location of aquitards combined with no vertical-expanse coverage of the aquifer thickness with observation wells limited the ability to obtain unique aquifer property values using the observation well data.

Before extended pumping degraded the specific capacity, R-66 produced 8.6 gpm for 30 min with 7.94 ft of drawdown for a short-term specific capacity of 1.08 gpm/ft. The lower-bound hydraulic conductivity computed from this information was 42.7 gpd/ft², or 5.7 ft/d, consistent with the pumping test value.

11.0 REFERENCES

The following list includes all documents cited in this report. Parenthetical information following each reference provides the author(s), publication date, and ER ID. This information is also included in text citations. ER IDs are assigned by the Environmental Programs Directorate’s Records Processing Facility (RPF) and are used to locate the document at the RPF and, where applicable, in the master reference set.

Copies of the master reference set are maintained at the NMED Hazardous Waste Bureau and the Directorate. The set was developed to ensure that the administrative authority has all material needed to review this document, and it is updated with every document submitted to the administrative authority. Documents previously submitted to the administrative authority are not included.


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Figure 1.0-1 Location of well R-66
Figure 7.0-1  Well R-66 apparent hydrograph

Figure 7.0-2  Well TW-3 hydrograph
Figure 7.0-3  Well TW-3 background correction

Figure 7.0-4  Well O-4 background
Figure 8.1-1  Well R-66 trial 1 drawdown

Figure 8.1-2  Well R-66 trial 1 recovery
Figure 8.2-1  Well R-66 trial 2 drawdown

Figure 8.2-2  Well R-66 trial 2 recovery
Figure 8.3-1  Well R-66 step-drawdown test

Figure 8.4-1  Well R-66 drawdown
Figure 8.4-2  Well R-66 drawdown—expanded scale

Figure 8.4-3  Well R-66 recovery
Figure 8.4-4   Well R-66 recovery—expanded scale

Figure 8.4-5   Well R-66 drawdown and recovery comparison
Figure 8.4-6  Theis analysis of TW-3 drawdown

Figure 8.4-7  Theis analysis of TW-3 recovery
Figure 8.4-8  Partial penetration analysis