Aquifer Test #1

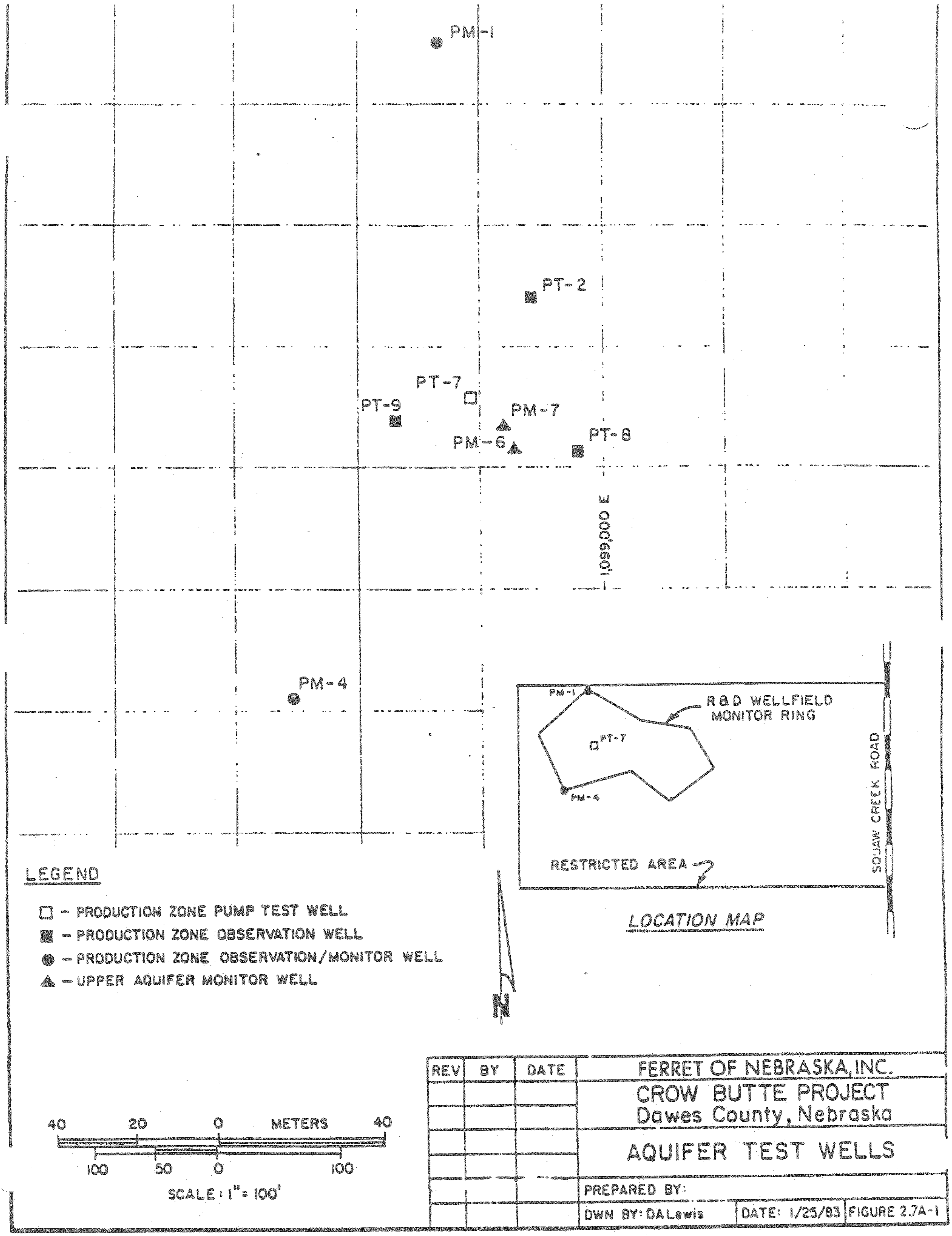
First Aquifer Test

The first aquifer test was conducted in the R&D wellfield during November, 1982. The pumping period was 50.75 hours and the recovery was monitored subsequently for 27.6 hours. Water levels in four production zone observation wells and two shallow Brule monitor wells were monitored. The following sections describe the results of that test and the methods of analysis used. Figure 2.7A-1 shows the relative locations of the wells used in the aquifer test.

Aquifer Test Well Pattern. The wells used for the aquifer test were located so that they could be incorporated into the pilot wellfield. Four of the R&D pattern wells were drilled and completed in the lower 15 to 20 feet (4.5 to 6.0 m) of the Basal Chadron Sandstone. They are numbered PT-2, PT-7, PT-8 and PT-9. Two of the production zone monitor wells were also drilled and completed in the same horizon. These two production zone monitor wells are designated PM-1 and PM-4. In addition to the production zone wells, two shallow aquifer monitor wells were installed into saturated upper sands of the outcropping Brule Formation. The deeper of the two is PM-6 and the other is assigned the number PM-7.

The original completion method used for the wells was the integral screen and cement basket completion. Some difficulties with the original 4 inch (10 cm) screen made it necessary to install 2 inch (5 cm) telescoping liners inside the 4 inch (10 cm) to control sand production.

Table 2.7A-1 lists the completion details for the pump test wells along with their distances from the pumping well, PT-7. The Chadron wells are completed only in the lower 15 to 20 feet (4.5 to 6.0 m) of the Basal Sandstone which has a total thickness of 30 to 45 feet (9 to 14 m). The effects of spherical flow as a result of partial penetration of the aquifer by the well screen are most apparent in the vicinity of the pumping well. As a general rule, horizontal flow conditions are assumed to exist at distances from the pumping well greater than 2 times the total aquifer thickness. For this situation, the drawdown data from wells at a distance of more than 60 to 90 feet (18 to 27 m) should be free from the influence



PM-1
PT-2
PT-7
PT-9
PM-7
PM-6
PT-8
1,099,000 E
PM-4
R&D WELLFIELD MONITOR RING
PM-1
PT-7
PM-4
RESTRICTED AREA
SQUAW CREEK ROAD
LOCATION MAP
LEGEND
□ - PRODUCTION ZONE PUMP TEST WELL
■ - PRODUCTION ZONE OBSERVATION WELL
● - PRODUCTION ZONE OBSERVATION/MONITOR WELL
▲ - UPPER AQUIFER MONITOR WELL
N
40 20 0 METERS 40
100 50 0 100
SCALE: 1" = 100'
REV
BY
DATE
FERRET OF NEBRASKA, INC.
CROW BUTTE PROJECT
Dawes County, Nebraska
AQUIFER TEST WELLS
PREPARED BY:
DWN BY: DALewis
DATE: 1/25/83
FIGURE 2.7A-1

TABLE 2.7A-A1

PUMP TEST WELL COMPLETION DATA
R & D PROJECT AREA

Well No.	Total Depth (ft)	Centralizer Depths (ft)	Basket Depth (ft)	Screen Interval (ft)	Distance To Pumping Well (ft)
PM-1	674.5	640,540,440,320,240, 160,120,60,Top	645	649.5-669.5	294
PM-4	674.5	10,40,80,115,215 315,415,515,615	637	641.5-646.5 654.5-669.5	289
PM-6	217.5	0, 60, 140, 180	193	196.0-211.0	56
PM-7	129.5	0, 40, 80	85	89.5 - 94.5 99.5 -104.5 109.0-114.0 119.5-124.5	35
PT-2	665.6	10,60,80,119,219, 319,419,519,619	641	641.0-656.0	93
PT-7	672.5	20,80,120,230,330, 430,530,630	648	649.0-664.0	0
PT-8	674.5	630,530,430,330, 230,130,70,30,8	650	653.0-668.0	94
PT-9	680.5	10,50,90,140,240, 340,440,540,640	656	659.0-674.0	66

of partial penetration. Well number PT-9 is the only production zone well closer than 93 feet (28 m) and PT-9 was not monitored during the aquifer test because of screen plugging.

The static water levels for the test area are given in Table 2.7A-2. As can be seen, the piezometric surface is essentially flat across the test pattern.

<u>Pump Test</u>. The center well of the pattern, PT-7, was equipped with a 7-1/2 HP submersible pump which was set at a depth of 620 feet (189 m). The pump discharge line was 1-1/4 inch iron pipe. Power was supplied by a 20 KVA diesel driven generator which ran continuously for the duration of the test. A one inch (2.5 cm) diaphragm valve was used as a flow control valve and two Badger flow totalizers were installed in the discharge line to meter the flow. Only one flow meter was used at any one time, keeping the second in reserve. The discharge line from the flow meters extended 500 feet (152 m) from the well head to insure that leakage down into the shallow aquifers did not occur.

TABLE 2.7A-2

STATIC WATER LEVEL IN THE CROW BUTTE
R & D PROJECT AREA

Well No.	Aquifer	Water Level Elevation * (feet-msl)
PM-1	Chadron	3754.3
PM-4	Chadron	3754.4
PM-6	Brule	3843.5
PM-7	Brule	3845.9
PT-2	Chadron	3754.6
PT-7	Chadron	3754.2
PT-8	Chadron	3754.4
PT-9	Chadron	3754.6

* Measured January 10, 1983.

A recording barometer was set up near the test area to monitor fluctuations in atmospheric pressure during the test. Measurements of the water levels in the pilot area wells were also made for a period of 8 days after the aquifer test wells had returned to static conditions. These data were compared with the variations in atmospheric pressure to determine the degree of correlation between atmospheric pressure and hydrostatic head in the aquifer. The barometric efficiency of the aquifer can be estimated by dividing the changes in water level by the concurrent changes in barometric pressure.

Each of the observation wells was equipped with an electric water level indicator and most measurements in each well were made with the same instrument. During the early stages of the test, a person was stationed at each well to take the measurements in rapid succession. Pumping began at 7:15 AM on 11/16/82 and was discontinued at 10:00 AM of 11/18/82; a period of 50.75 hours. A discharge rate of 24 gpm (91 l/min) was chosen for the test. The overall average flow rate was 23.8 gpm (90 l/min) and the fluctuations were generally less than 0.3 gpm (1.1 l/min) or 1.3 percent. Water level measurements were taken at 1, 2 and 5 minutes, then at 5 minute intervals for the first 30 minutes of the test with regularly increasing intervals to 4 hours after 24 hours of elapsed time. Drawdowns were generally smooth and symmetrical and there were no equipment failures or interruptions in the test.

Methods of Data Analysis

Five different approaches have been used to analyze the data from the pump test. The original permit application included analyses based on Theis' Nonequilibrium Method, the Modified Jacob Nonequilibrium Method, and Theis' Recovery method. These analysis techniques, all assuming no leakage, were chosen based on the geology of the site.

Implicit to the application of these types of analyses are a series of assumptions that must be considered of the results. The assumptions underlying the methods used herein are listed below.

- The aquifer has seemingly infinite areal extent,
- The aquifer is homogeneous, isotropic and of uniform thickness over the area influenced by the pumping test,
- Prior to pumping, the piezometric surface is nearly horizontal over the area influenced by the pump test,
- The aquifer is pumped at a constant discharge rate,
- The pumped well penetrated the entire aquifer and thus received water from the entire thickness of the aquifer by horizontal flow,
- The water removed from storage is discharged instantaneously with decline in head,
- The aquifer is fully confined (no leakage or deviation from storage),
- The flow to the well is in unsteady state,
- Storage in the well can be neglected,
- The argument (u) of the well function is less than 0.01 (Modified Jacob and Theis Recovery methods only).

The first three assumptions are seldom entirely satisfied in nature, although small deviations are not prohibitive. The fourth assumption is more easily satisfied by careful control of the pump discharge rate. The next qualification, of full aquifer penetration by the pumping well, is not practical if the wells are to be used in an in situ mining wellfield; but by using observation wells at sufficient distances (greater than twice the aquifer thickness), the effects of spherical flow are eliminated. Emperical evidence from aquifer tests has justified the last assumption (constant storage coefficient).

Based on significant deviation of the pump test data from the Theis type curve in the original analysis, the USNRC questioned the use of a non-leaky analysis method on the data. In response to those concerns, the data were analyzed using a two-stage fit to the Theis type curve. This two-stage analysis was based on changes in aquifer thickness and permeability. In addition, an analysis of leakage was performed based on laboratory testing of core samples.

After further discussions with the USNRC, the data were analyzed again using the Modified Hantush method. This analysis method takes into account fluid derived from storage in the confining bed(s). Since all confining beds exhibit some leakage or loss from storage, however small, and since the Theis equation is a special case of the Modified Hantush equations, use of the Modified Hantush analysis was considered proper for the data available.

The water level in well PT-9 did not respond during the pump test. After the test, the screen was removed from PT-9 and found to be completely plugged with silt and clay sized material. This material is thought to have accumulated due to the use of pumping as the only well development technique. The screen was replaced and the well is now functioning properly.

Water levels in the two shallow monitor wells showed no drawdown during the period of the pump test. Figure 2.7A-2 shows the water level fluctuations in the shallow wells during the period of the test. It is therefore concluded that the confining layers between the production zone and upper water bearing zones do not permit leakage. (Note: Well PM-7 shows a water level change at the beginning of the test. It was determined that a faulty probe was being used during the first two hours of the test. Once this was discovered, the water levels for the remainder of the test were measured with the proper probe).

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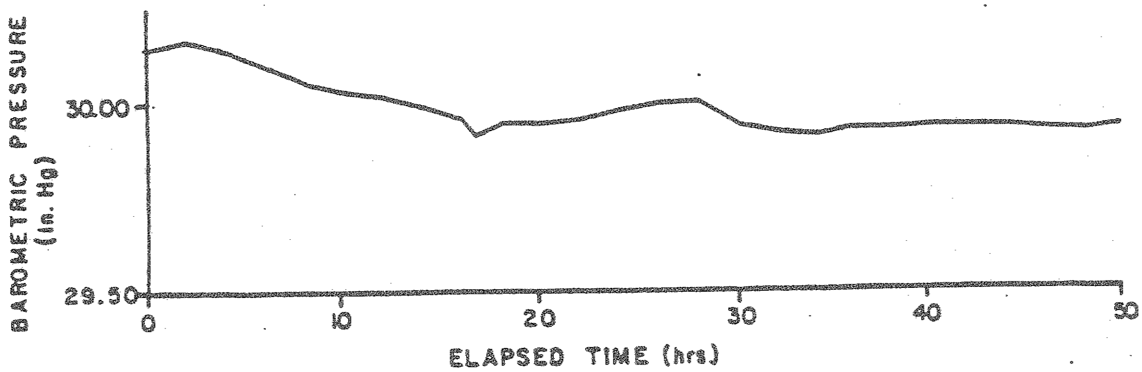
CROW BUTTE PROJECT

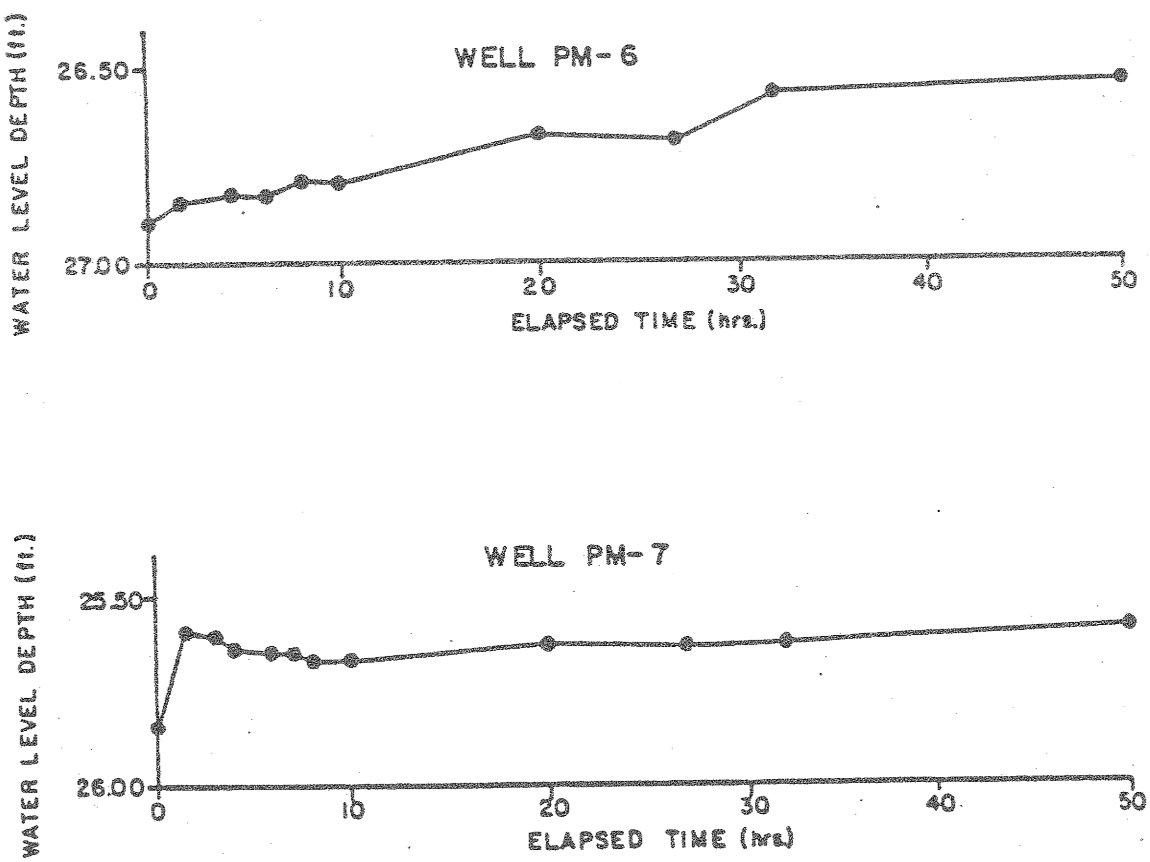
Dawes County, Nebraska

BAROMETRIC PRESSURE vs. ELAPSED TIME OF PUMPING TEST
11/16/82 – 11/18/82



(A)

SHALLOW AQUIFIER WATER LEVELS vs. ELAPSED TIME OF PUMPING TEST



(B)

FIGURE 2.7A-2

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1-14-83

The fluctuations in water levels in the wellfield were measured after the test from 12/6/82 to 12/13/82. Those data were compared with the barometric pressure changes for the same period. An estimate of the barometric efficiency of the aquifer can be obtained from that comparison. Barometric efficiency is defined as the ratio of the water level changes in a well and the concurrent fluctuations in atmospheric pressure. Both values are usually expressed in meters of water as calculated from the data for the 8 day period of measurement. The barometric efficiency of the Basal Chadron Sandstone was 0.40. A graphical comparison of those data is included as Figure 2.7A-3. The effects of barometric pressure changes are not noticeable during the early part of a pump test but are often responsible for the minor fluctuations in drawdown during the latter portion of the test when the rate of change in drawdown is very small. The following sections summarize the hydrologic analyses performed..

Theis' Nonequilibrium Method. Water levels in the observation wells continued to decline for the duration of the test indicating a continuously expanding cone of depression. Under those circumstances, the unsteady state methods of analysis are generally employed. One of the most common of these methods is the Theis nonequilibrium curve matching technique.

The drawdown data "s" for each well are plotted on log-log coordinate paper versus r^2/t: where r is the distance from pumping well to the observation well and t is the time in minutes since the pumping started. The curves are then compared to a standard non-leaky artesian type curve which is a log-log plot of the "well function" W(u) and its argument u.

The results of the Theis curve matching method produce an average value for transmissivity, T, of 3,724 gal/day-ft ($5.36x10^{-4} m^2/sec$) and an average storage coefficient S, of $9.66x10^{-5}$. The variation in the four estimated values of T was less than 4 percent. The results of the Theis analysis are given in Table 2.7A-3.

The results of the analysis of the recovery data are also presented in Table 2.7A-3. The average value of T is 3,936 gal/day-ft ($5.66x10^{-4} m^2/sec$) for this method which is slightly higher than the values from the previous

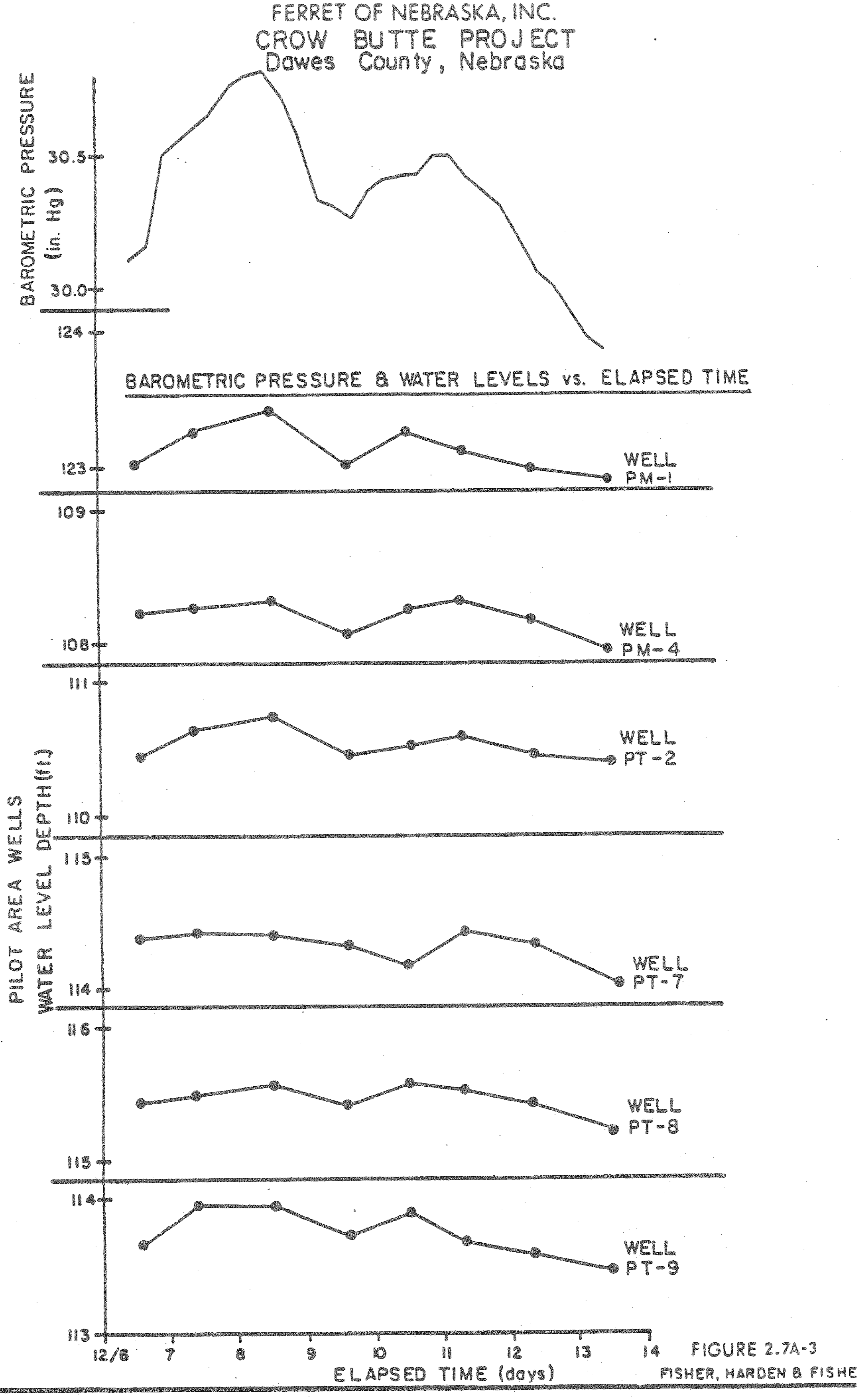

FIGURE 2.7A-3

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TABLE 2.7A-3

ESTIMATED AQUIFER PARAMETERS

Well No.	Theis' Method T (gpd/ft)	Theis' Method T (m^2/sec)	Theis' Method S	Jacob's Method T (gpd/ft)	Jacob's Method T (m^2 sec)	Jacob's Method S	Theis' Recovery Method T (gpd/ft)	Theis' Recovery Method T (m^2/sec)	Theis' Recovery Method S
PT-2	3767	5.42x10^{-4}	1.24x10^{-4}	3727	5.36x10^{-4}	1.34x10^{-4}	3662	5.27x10^{-4}	-------
PT-8	3793	5.45x1-$^{-4}$	1.20x10^{-4}	3840	5.52x10^{-4}	1.23x1-$^{-4}$	4010	5.77x10^{-4}	------
PM-1	3595	5.17x10^{-4}	6.51x10^{-5}	3899	5.61x10^{-4}	5.85x10^{-5}	3984	5.73x10^{-4}	-------
PM-4	3742	5.38x10^{-4}	7.72x10^{-5}	3984	5.73x10^{-4}	7.28x10^{-5}	4087	5.88x10^{-4}	-------
MEAN	3724	5.36x10^{-4}	9.66x10^{-5}	3863	5.56x10^{-4}	9.71x10^{-5}	3936	5.66x10^{-4}	-------

analyses. Here again, conditions appear to be horizontally isotropic. The fact that the recovery curves do not go precisely through s"=0 and intersect the drawdown axis at a value <0 suggests a slight variation in the value of S for the drawdown and S" for the recovery. This can be expected as no aquifer is perfectly elastic and the rate of rebound often shows some hysteresis.

Two-Stage Theis Nonequilibrium Analysis. The value of transmissivity T, is the product of hydraulic conductivity k, and the aquifer thickness (b). It was assumed that both of these quantities were virtually constant throughout the area of the aquifer that was affected by the aquifer-test pumping. The thickness of the aquifer at the pumping well PT-7, is 41 feet (12.5 m). At a distance of 93 feet (28.3 m) to the north at well PT-2, the aquifer thickness is 32 feet (9.7 m). Core logs of both holes reveal a marked change in the grain size and sorting of the material comprising the aquifer. Grain size and sorting are controlling factors of formation permeability. Further examination of the geology of the pump test area shows a change in aquifer thickness from 32 to 49 feet (9.7 to 14.9 m) or 53%. If the value of k remains constant, the value of T would then vary 53%. Values for k however, vary widely in braided stream deposits like the Basal Chadron Sand.

This variation in both hydraulic conductivity and aquifer thickness does not strictly follow the assumptions implicit in the methods of data analysis and therefore must be taken into consideration. Variations in aquifer thickness of 30 to 50 percent cannot be ignored. Changes in thickness can be treated by matching the Theis curve to the early and the late data independently, calculating a T value for each segment of the curve. The results of this analysis are given in Table 2.7A-4. The average T for the early part of the curve is 2,450 gal/day-ft and for the later part of the curve is 3,760 gal/day-ft. This represents an increase in transmissivity of approximately 53%, which is comparable to the changes in aquifer thickness.

TABLE 2.7A-4

ESTIMATED AQUIFER PARAMETERS
TWO-STAGE THEIS ANALYSIS

	Early		Late	
WELL	T(gpd/ft)	S	T(gpd/ft)	S
PT-8	2116	$3.0x10^{-4}$	3667	$1.7x10^{-4}$
PT-2	2500	$2.6x10^{-4}$	3618	$1.5x10^{-4}$
PM-1	2806	$7.2x10^{-5}$	3767	$6.6x10^{-5}$
PM-4	2391	$1.0x10^{-4}$	3986	$8.0x10^{-5}$
MEAN	2453	$1.8x10^{-4}$	3759	$1.2x10^{-4}$

Modified Hantush Analysis. In this analysis the following techniques were used to determine the aquifer/aquitard characteristics:

- Modified Hantush (1965) method for analyzing pumping test data for aquifers influenced by storage from leaky confining beds.
- Hantush (1966) method for defining the major and minor axes of transmissivity in an aquifer.
- Theory of consolidation (Scott, R.F. 1963).

The following analysis is based on *Aquifer/Aquitard Analysis, Crow Butte ISL Uranium Project* by D'Appolonia Consulting Engineers, October, 1983.

1. **Transmissivity and Storage Coefficient of the Basal Chadron Aquifer.** The Modified Hantush method was applied to calculate the transmissivities and storage coefficients for the Basal Chadron aquifer. The method is appropriate for the situation when part of the flow from the pumped aquifer comes as a contribution from confining beds. The drawdown versus time curves, Figures 2.7A-4 to 2.7A-7 give the apparent indication of leakage, especially noticeable at the late times. The observation wells completed in the overlying sands of the Brule Formation do not show response to the pumping in the Basal Chadron.

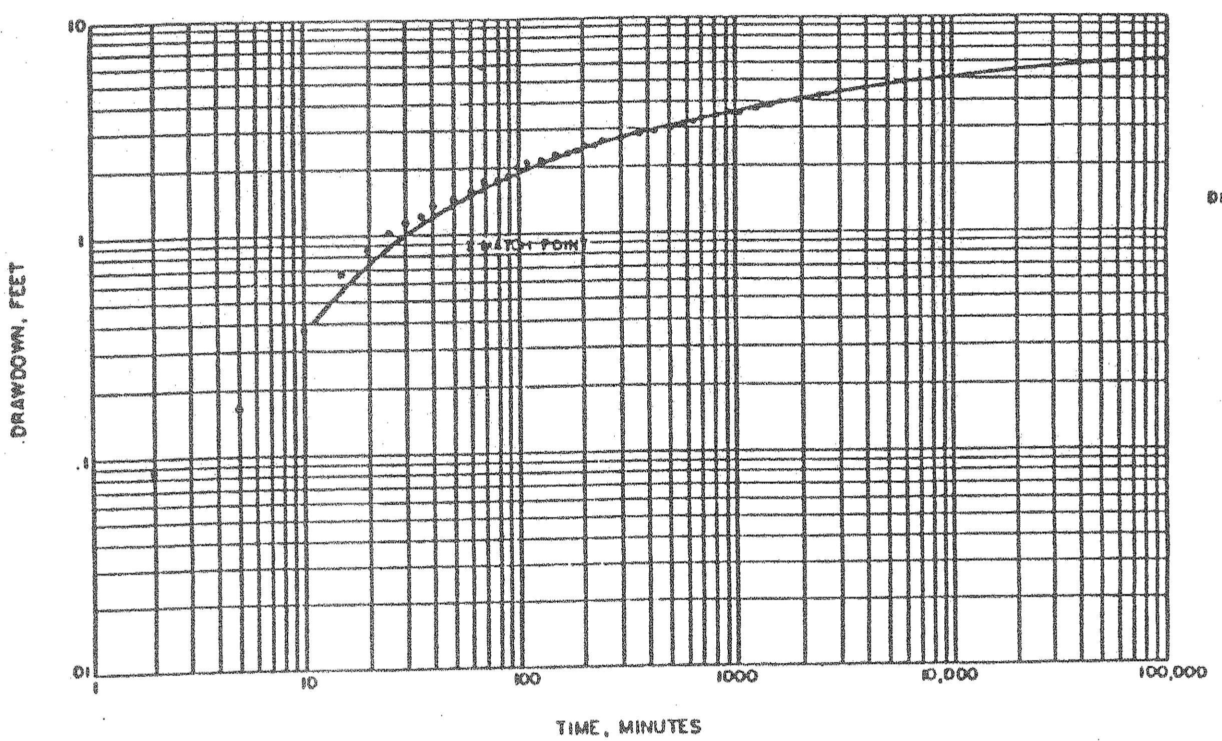
The curve matching technique was used to analyze the data from the observation wells. A log-log plot of drawdown versus elapsed time was laid over the family of type curves which characterize the various possible degrees of leakage from the aquitard to the pumped aquifer. The curve which best fit the data by keeping the axes parallel was determined (Figures 2.7A-4 to 2.7A-7). The designation of the type curve best fitting the drawdown values was recorded and an arbitrary point common to both graphs was selected. The coordinates of the matching point were recorded. The following equations were applied to define the aquifer properties, using match point coordinates:

(Eq. 1)

$$T = \frac{Q}{4\pi s} H(u,\beta)$$

and

(Eq. 2) $S = 4Ttu/r^2$



$\beta = 0.02$

$H(u, \beta) = 1.0$

$\frac{1}{u} = 10, \; u = 0.1$

$s = .92$ ft

$t = 78$ min

DISTANCE FROM THE PUMPING WELL

$r = 294$ ft

$T = \frac{Q}{4 \pi s} H(u, \beta)$

$T = \frac{24}{4 \pi (.92)} \times 1.0 \times 1440 = 399 \text{ ft}^2/\text{day}$

$S = \frac{4 T t u}{r^2}$

$S = \frac{4 \times 399 \times 78 \times 0.1}{(294)^2 \times 1440} = 1.0 \times 10^{4}$

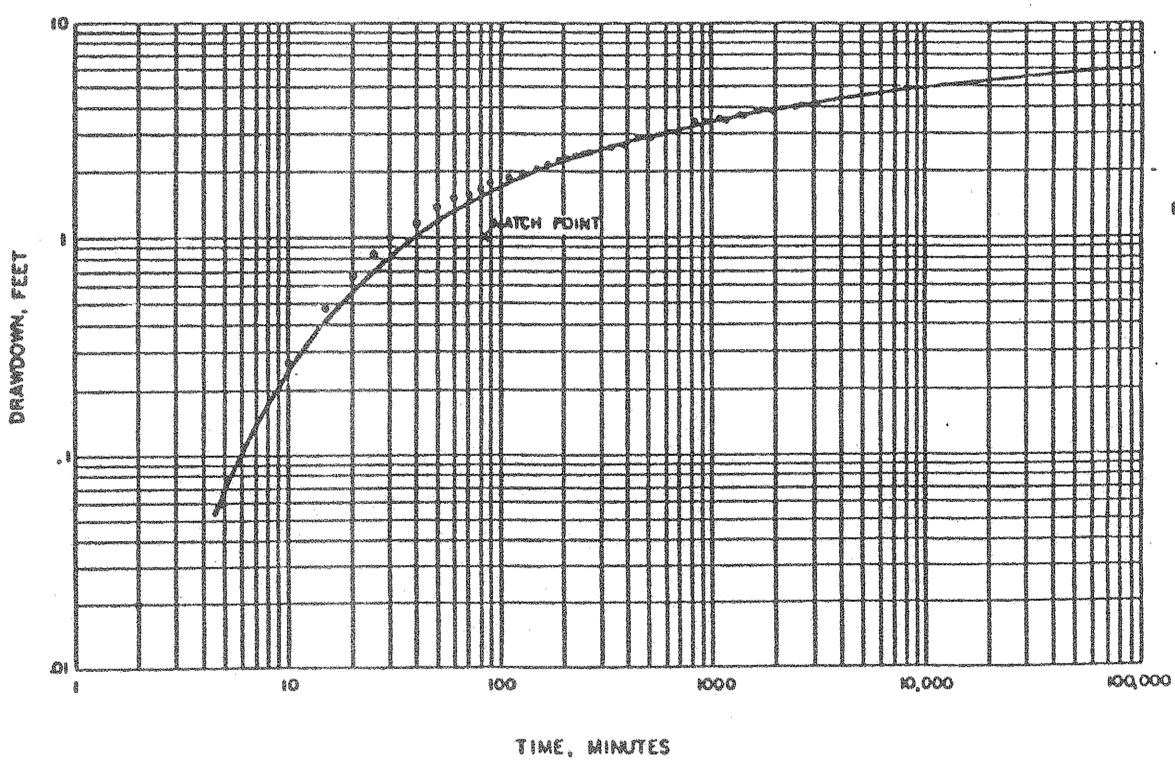
FIGURE 2.7A-4

AQUIFER ANALYSIS BY
MODIFIED HANTUSH METHOD
OBSERVATION WELL PM-1

PREPARED FOR

WYOMING FUEL COMPANY
LAKEWOOD, COLORADO

DAPPOLONIA



$\beta = 0.05$

$W(u, \beta) = 1.0$

$\frac{1}{u} = 10,\ u = 0.1$

$s = 1.0$ ft

$t = 83$ min

DISTANCE FROM THE PUMPING WELL:

$r = 288.75$ ft

$T = \frac{Q}{4\pi s} W(u, \beta)$

$T = \frac{24}{4\pi(1.0)} \times 1.0 \times 1440 = 367\ \text{ft}^2/\text{day}$

$S = \frac{4Ttu}{r^2}$

$S = \frac{4 \times 367 \times 83 \times 0.1}{(288.75)^2 \times 1440} = 1.0 \times 10^{-4}$

FIGURE 2.7A-5

AQUIFER ANALYSIS BY
MODIFIED HANTUSH METHOD
OBSERVATION WELL PM-4

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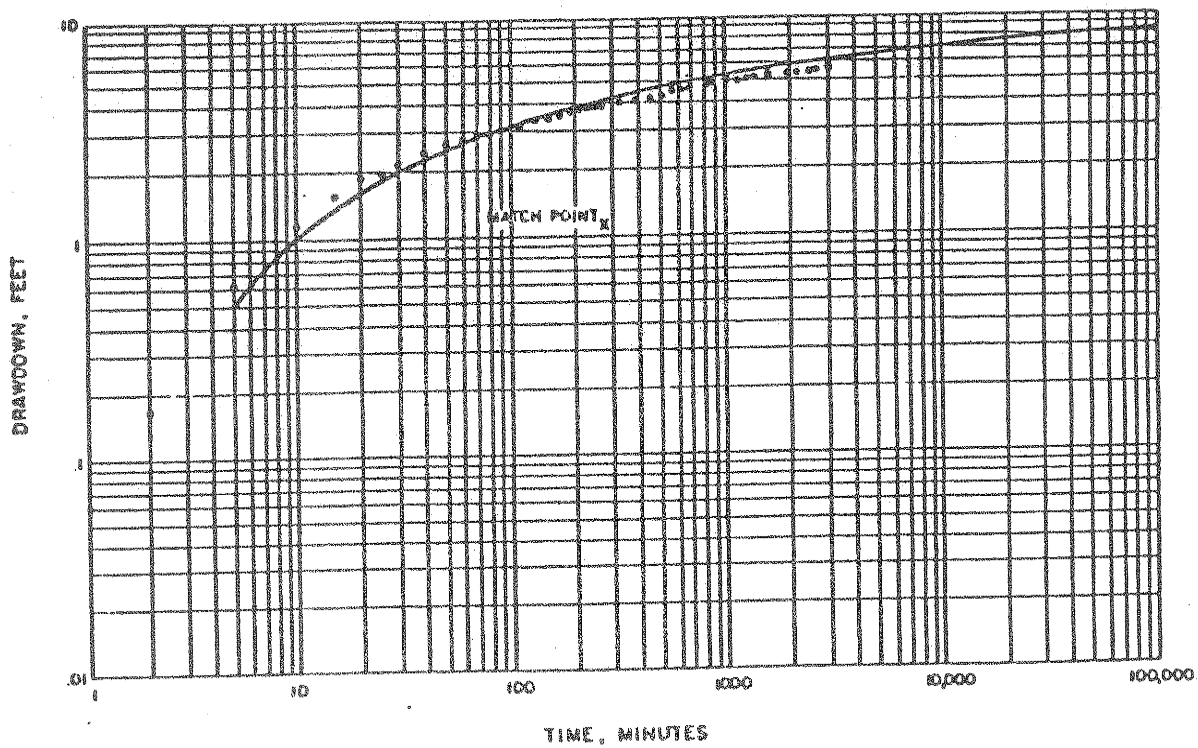
LAKEWOOD, COLORADO

D'APPOLONIA



$\beta = 0.02$

$M(u, \beta) = 1.0$

$\frac{1}{u} = 100, \; u = .01$

$s = 1.0 \text{ ft}$

$t = 200 \text{ min}$

DISTANCE FROM THE PUMPING WELL

$r = 93.49 \text{ ft}$

$$T = \frac{Q}{4\pi s} M(u, \beta)$$

$$T = \frac{24}{4\pi(1.0)} \times 1.0 \times 1440 = 367 \text{ ft}^2/\text{day}$$

$$S = \frac{4Ttu}{r^2}$$

$$S = \frac{4(367)200(0.01)}{(93.49)^2 \times 1440} = 2.3 \times 10^{-4}$$

AQUIFER ANALYSIS P-
MODIFIED HANTUSH METHOD
OBSERVATION WELL PT 2

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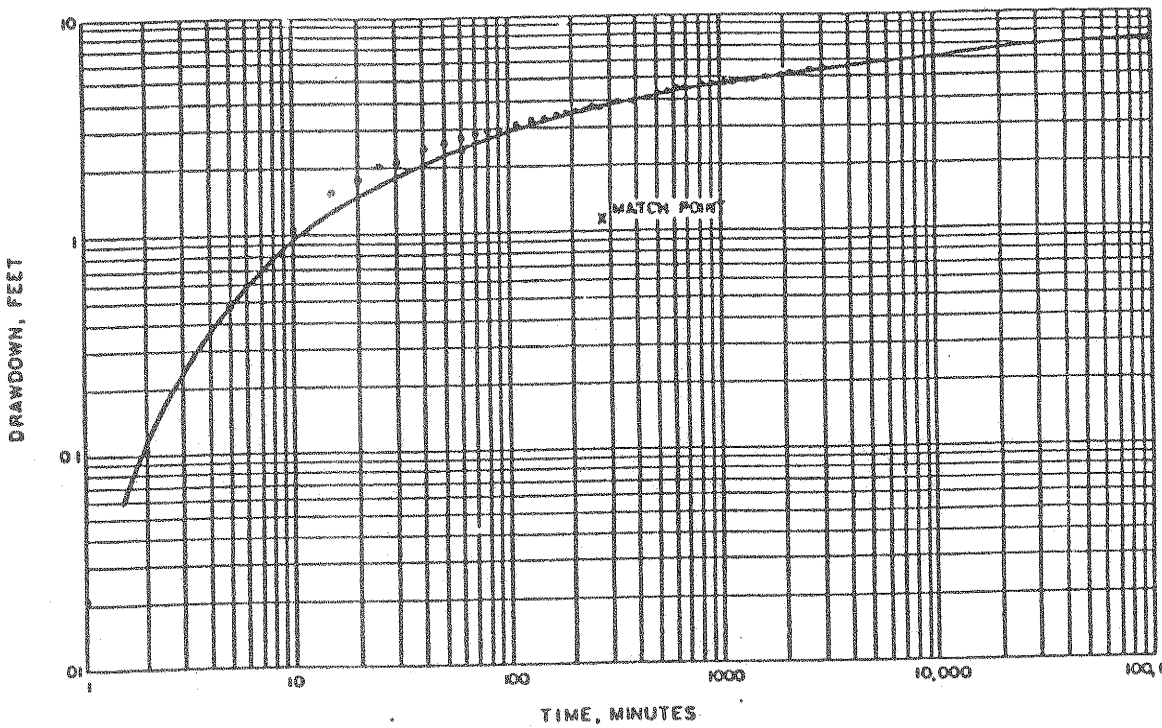
FIGURE 2.7A-6



$\beta = 0.05$

$H(u, \beta) = 1.0$

$\frac{1}{u} = 100$, $u = 0.01$

$s = 1.2$ ft

$t = 275$ min

DISTANCE FROM THE PUMPING WELL:

$r = 93.69$ ft

$$T = \frac{Q}{4 \pi s} H(u, \beta)$$

$$T = \frac{24}{4 \pi (1.2)} \times 1.0 \times 1440 = 306 \text{ ft}^2/\text{day}$$

$$S = \frac{4 T t u}{r^2}$$

$$S = \frac{4(306)275(0.01)}{(93.69)^2 \times 1440} = 2.7 \times 10^{-4}$$

AQUIFER ANALYSIS BY
MODIFIED HANTUSH METHOD
OBSERVATION WELL PT-8

PREPARED FOR

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LAKEWOOD, COLORADO

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FIGURE 2.7A-7

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Where:

T = transmissivity
Q = pumping rate
H (u,ß) = Hantush's leaky aquifer function
s = drawdown
S = storage coefficient
t = pumping time
u = well function
r = distance from pumping well

The transmissivity measured at four observation wells (PM-1, PT-2, PT-8, and PM-4 ranged from 306 ft^2/day to 399 ft^2/day (2289-2985 gpd/ft) during the pumping period. The storage coefficients ranges from 9.9×10^{-5} to 2.7×10^{-4} (Table 2.7A-5).

The drawdown data as shown in Figures 2.7A-4 to 2.7A-7 do not appear affected by partial penetration of the production well, which is in agreement with the theory (Hantush, 1961) that vertical flow to a partially penetrating well is not significant at the observation well location when the distance between the pumping and observation well exceeds two thicknesses of the aquifer.

2. **Directional Transmissivity of the Basal Chadron Aquifer.** Most aquifers do not exhibit the same transmissivity in all directions in the horizontal plane, but rather show some horizontal anistropy. Typically, this anistropy can be described by an ellipse of transmissivity with major and minor axes corresponding to the directions of maximum and minimum transmissivities. Hantush (1966) presented a method for defining these axes. The method requires transmissivity values derived from observation wells located along three different radial lines from the pumping well, and is a trigonometric solution for an ellipse, given three points along its perimeter.

TABLE 2.7A-5

AQUIFER PROPERTIES CALCULATED BY THE HANTUSH METHOD

OBSERVATION WELL	TRANSMISSIVITY (feet²/day)	TRANSMISSIVITY (gpd/ft)	STORAGE COEFFICIENT S
PM-1	399	2985	$9.9X10^{-5}$
PM-4	367	2746	$1.0x10^{-4}$
PT-2	367	2746	$2.3x10^{-4}$
PT-8	306	2289	$2.7x10^{-4}$
Mean	360	2692	$1.75x10^{-4}$

In addition to the orientation and magnitude of the major and minor axes, the method also provides a value for the effective (or geometric mean) transmissivity, and permits the calculation of transmissivity in the direction of flow. If the saturated thickness of the aquifer is generally uniform, the directional hydraulic conductivity of the aquifer will correspond more or less with the directional transmissivity.

The directional transmissivity for the Basal Chadron aquifer was determined from four observation wells. The major axis of transmissivity lies along an azimuth of 2 degrees and has the magnitude of 401 ft^2/day (3000 gpd/ft). The minor axis of transmissivity has an azimuth of 92 degrees with a magnitude of 290 ft^2/day (2169 gpd/ft). The geometric mean of transmissivities is 341 ft^2/day (2551 gpd/ft). The major and minor axes of hydraulic conductivity coincide with the transmissivity axes and have magnitude of 10 ft/day and 7.25 ft/day respectively based on a Basal Chadron Sandstone nominal thickness of 40 feet over the area tested (Table 2.7A-7). The geometric mean hydraulic conductivity is 8.52 ft/day.

3. **Properties of the Aquitards.** The results of the laboratory testing performed on core samples from the core hole C6C, the only such samples available, were utilized in the following section of this report. Since no monitoring wells were installed in the Middle Chadron Formation, no aquitard permeability data are available from the pump test.

Information from the laboratory tests used in this report include:

- for Pierre Shale
  - vertical hydraulic conductivity - $K_v = 9.6 \times 10^{-9}$ ft/day
  - coefficient of consolidation - $C_v = 6.3 \times 10^{-3}$ cm^2/sec
- for Red Clay
  - vertical hydraulic conductivity - $K_v = 7.8 \times 10^{-7}$ ft/day
  - coefficient of consolidation - $C_v = 1.9 \times 10^{-3}$ cm^2/sec
- for Sandy Claystone
  - vertical hydraulic conductivity - $K_v = 8.2 \times 10^{-7}$ ft/day
  - coefficient of consolidation - not available

The laboratory test data are summarized in Table 2.7A-6.

4. **Analysis of the Aquifer/Aquitard Interaction.** Examination of the drawdown/time curves plotted for observation wells indicated that some leakage from confining beds occurred during the pumping test. To quantify

TABLE 2.7A-6

SUMMARY OF THE AQUITARD PROPERTIES

	Vertical Hydraulic Conductivity[1],K (feet/day)	(cm-sec)	Coeffecient of Consolidation[2] C_v (cm^2/sec)
Red Clay	$7.8x10^{-7}$	$2.8x10^{-10}$	$1.9x10^{-3}$
Sandy Claystone	$8.2x10^{-7}$	$2.9x10^{-10}$	Not Available
Pierre Shale	$9.6x10^{-8}$	$3.4x10^{-11}$	$6.3x10^{-3}$

(1) From laboratory testing on core samples from C6C corehole by Core Laboratories.

(2) From laboratory testing on core samples from C6C corehole by Woodward-Clyde Consultants.

the aquifer/aquitard interaction which resulted in release of the water from the confining beds when the drawdown in Basal Chadron aquifer occurred, the following analysis of aquifer/aquitard interactions were performed.

To estimate the drawdown as a function of distance from the pumping wells, a drawdown-distance curve was simulated for the aquifer properties presented in Table 2.7A-5. The drawdown equation used to develop the drawdown-distance curve was based on the modified Hantush theory for a leaky aquifer:

(Eq. 3)

$$s = \frac{\;}{4\pi T} H(u,\beta)$$

(Eq. 4)

$$u = r^2 S/4tT$$

Where:

s = drawdown
Q = pumping rate
T - transmissivity (isotropic)
S = storage coefficient
t = pumping time
r = distance of observation from pump well
$H(u,\beta)$ = Hantush leaky well function
u = well function
β = type curve parameter for leaky aquifer analysis.

The simulated distance-drawdown curve for Basal Chadron Aquifer is presented in Figure 2.7A-8. The observed drawdowns are also shown in this figure; they are in reasonable agreement with the simulated drawdown.

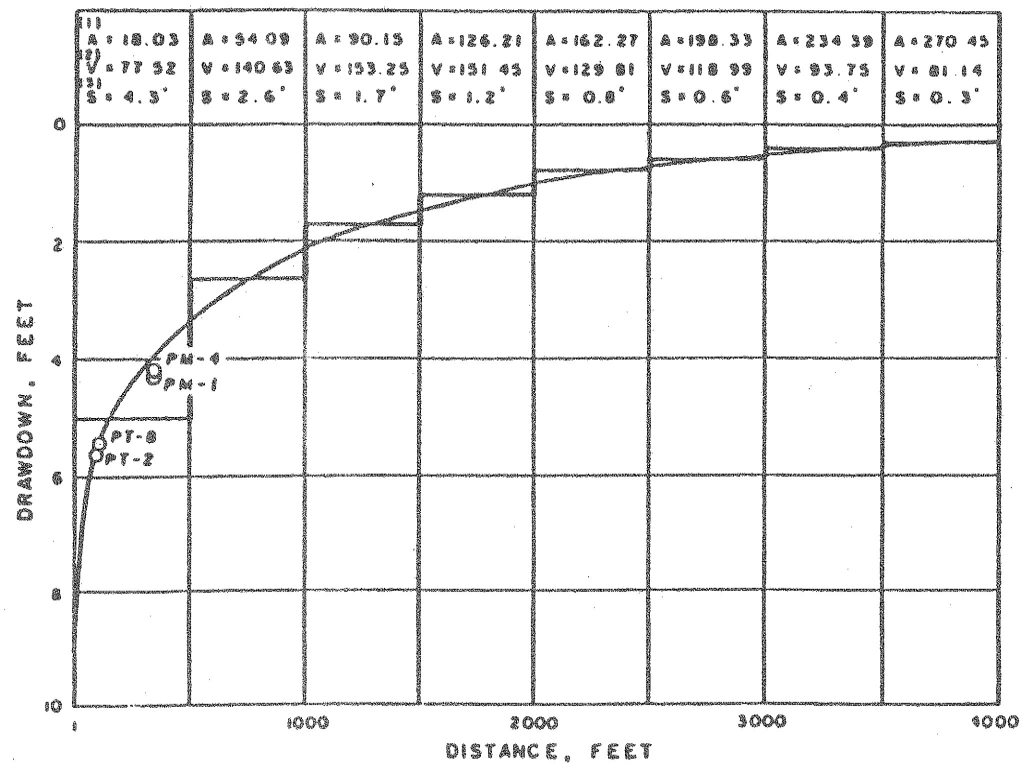
In the process of estimating the magnitude of leakage from the upper confinement both the Red Clay and Sandy Claystone, i.e., two strata immediately overlying the Basal Chadron aquifer, were examined. Initially the permeability of the system comprised of the Red Clay and Sandy Claystone was calculated from the relationship:

(Eq. 5)

$$K_{Av} = \frac{b'}{\frac{b'1}{K'_{z(1)}} + \frac{b'2}{K'_{z(2)}}}$$

Where:

K_{Av} = average vertical hydraulic conductivity of the system
b' = thickness of the system
b'_1, b' = thickness of the different strata comprising the system
$K'_z(1)$...$'_z(2)$ = vertical hydraulic conductivities of strata comprising the system.



AREA AFFECTED BY PUMPING

A_t = 1154 ACRES

TOTAL LEAKAGE FROM UPPER CONFINEMENT

V_t = 947 GALLONS

(1) ACRES

(2) GALLONS

(3) FEET

FIGURE 2.7A-8

SIMULATED DISTANCE
DRAWDOWN CURVE
AND INFLOWS FROM
UPPER AQUITARD

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WYOMING FUEL COMPANY
LAKEWOOD, COLORADO

The average hydraulic conductivity of the entire system was found to be almost the same as the hydraulic conductivity of the Red Clay. Furthermore, from the analysis of the aquifer/aquitard interaction from the formation consolidation standpoint, it is apparent that during the period of the pumping test, the water released from the upper aquitard is entirely from the Red Clay. Pore pressure changes at the bottom of the Red Clay did not propagate through the clay into the overlying sandy claystone over the pumping test period. Applying the theory of consolidation (Scott, 1963), the volume of water which could be liberated from the Red Clay under induced drawdown was calculated from the relationship:

(Eq. 6)

$$Q_T = \frac{2\ K_v U_i}{\gamma\ w \sqrt{\pi}\ C_v} \quad \sqrt{t}$$

Where:

Q_T = volume of water released from the confining bed during the time t
K_v = vertical hydraulic conductivity of the confining bed
w = unit weight of water
U_i = induced change in effective overburden pressure, proportional to drawdown (s = U w)
C_v = coefficient of consolidation
t = time since drawdown occurred
s = drawdown

The analysis showed that Red Clay could release one gallon of water per one foot of drawdown per acre during the 2.09 days (i.e., during the entire pumping test). Using the values of drawdown for a given distance from the pumping well presented in Figure 2.7A-8 and the volumes of water which could be released from confinement, the overall contribution from aquifer upper confinement to the flow produced during the pumping test was calculated. The results of calculations are also illustrated in Figure 2.7A-9. The volume of water released from the Red Clay during the pumping test was thus computed to be about 1,000 gallons. This constitutes

The contribution from the Pierre Shale owing to its lower hydraulic conductivity (approximately one order of magnitude less than the upper confinement)(Table 2.7A-6) would be significantly smaller - about 0.06 gallon of water per foot of drawdown per acre - during the entire pumping test. Figure 2.7A-9 illustrates the relationship between volume of inflow

DRAWN BY	D J Rodriguez	10 31 83	CHECKED BY	RSP	10/31/83	DRAWING NUMBER	RM83-1721-A2
			APPROVED BY	JTG	10/31/83		

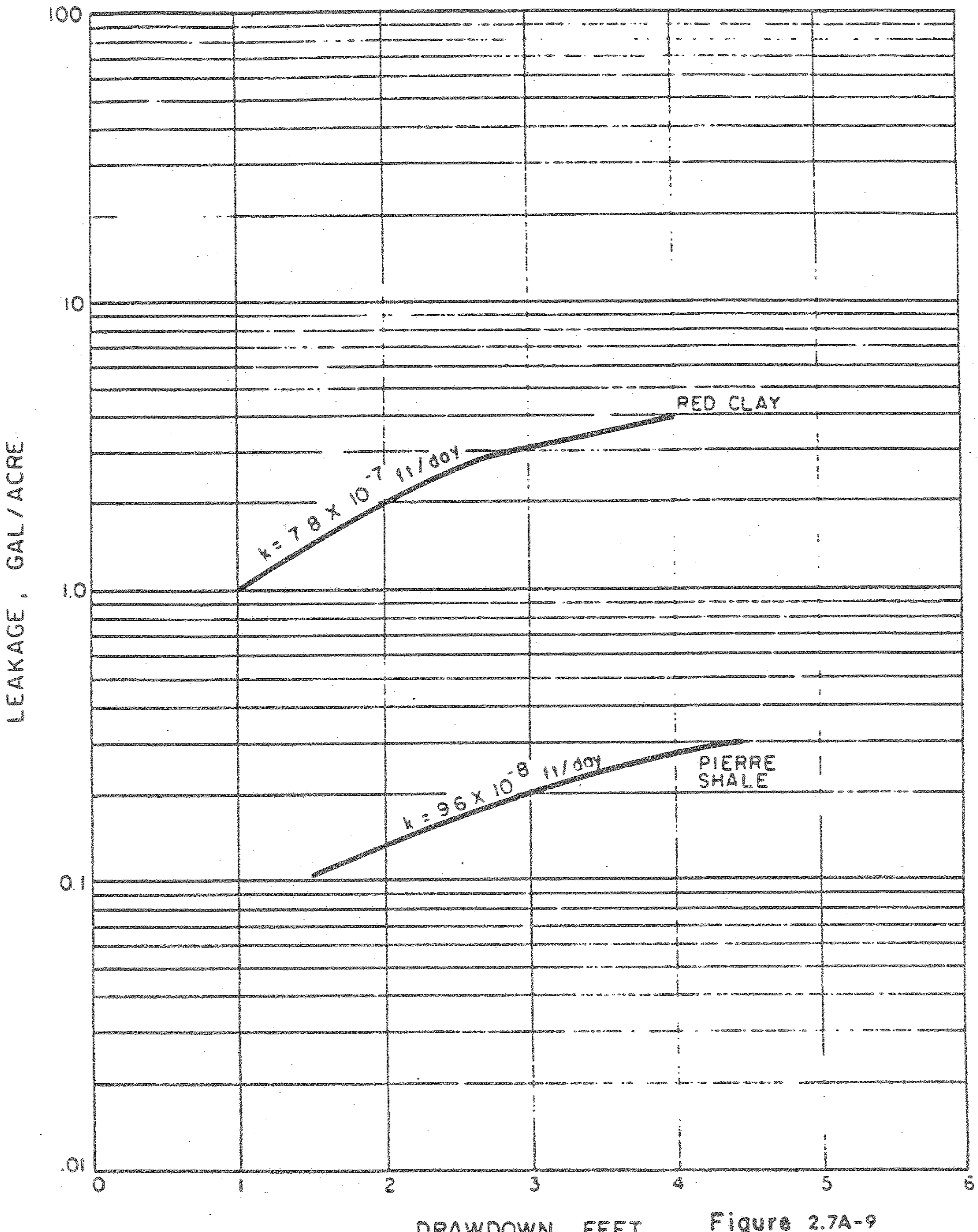

Figure 2.7A-9
LEAKAGE FROM AQUITARD VS DRAWDOWN
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from the confining Red Clay and Pierre Shale versus drop in the hydraulic head at the aquifer/aquitard contact.

In the above analysis, the transient nature of drawdown versus time was not considered in the analysis. In other words, the maximum drawdowns as observed or simulated for the final phase of the pumping test were assumed to persist for the duration of the pumping test. This is conservative in that it overpredicts the volume of water released.

For time periods extending well beyond the pumping test period, the rate of water released from the aquitard will be less than indicated above, assuming equal drawdown conditions. Quantification of this rate involves an analysis different from that represented in Equation 6.

Two factors which were used to further characterize the degree of confinement are the leakage factor (B) and the hydraulic resistance (c). The leakage factor was defined by Hantush (1964) as:

(Eq. 7) $B = [Kb/(K_{z'}/b')]^{1/2}$

Where:

B = leakage factor
K = hydraulic conductivity of aquifer
b = thickness of aquifer
$K_{z'}$ = vertical hydraulic conductivity of aquitard
b' = thickness of aquitard

The leakage factor has units of length. The greater the value of B, the less the contribution of leakage to the water pumped from the aquifer. For the 15 feet of immediate upper confinement comprised of the Red Clay, B has a value of about 8.1×10^4 feet, which is very large. The hydraulic resistance was defined by Kruseman and DeRidder (1970) as:

(Eq. 8) $c = b'/K_{z'}$

and has units of time. When multiplied by the porosity of the aquitard, the time that a molecule of water would take to pass through the given thickness of the aquitard under a unit gradient could be computed. The hydraulic resistance for the 15 foot thick section of the Red Clay immediately overlying the Basal Chadron sandstone is 53,000 years. To

calculate travel time through the confinement, an effective porosity value of 22 percent was used. This value is based on a measurement of effective porosity performed on a core sample of Red Clay. Only the Red Clay was considered in the analysis, due to its very low permeability and the short time of pumping. Assuming an effective porosity of 22%, the travel time through the 15 foot thick section of the aquitard under unit gradient would be 12,000 years.

5. **Ground Water Movement Within the Investigated Area.** The examination of the average ground water levels in the eight wells in Figure 2.7A-4 completed in the Chadron aquifer shows that the direction of the flow is toward the north and the dip of the potentiometric surface is 0.04 percent.

Using a directional hydraulic conductivity of 10 ft/day and an assumed effective porosity of 29 percent, the average pore velocity across the R&D site was computed to be about 5.0 ft/yr. The ground water flux across the site was computed to be 0.16 ft^3/day per unit width of the aquifer.