Mini-Report #5

ANALYSIS OF DRILLING RESPONSE AT THE HANFORD SITE

Basalt Waste Isolation Project
Subtask 2.5
Numerical Evaluation of Conceptual Models

Prepared by

Terra Therma Inc.

for

Nuclear Waste Consultants

June, 1986

TERRA THERMA, INC.

WATER CONSULTANTS AND ENGINEERS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

1.0 INTRODUCTION

The majority of in situ hydrologic tests conducted at the BWIP Site have been single borehole tests. These tests have provided reconnaisance level information on site hydrologic conditions. However, a high degree of uncertainty exists in using the results of single borehole tests to predict large-scale hydraulic properties of the layered basalt system. Multiple borehole tests measure large-scale (bulk) hydraulic properties and thus provide hydraulic parameter values which are more suitable for a site performance modeling. In the future, DOE plans to conduct large-scale hydraulic stress (LHS) tests of this type as an integral part of site characterization. To date, however, only a very limited number of multiple borehole tests have been performed at the BWIP Site.

Drilling and completion activities, associated with construction of monitor wells at the BWIP Site, have commonly involved withdrawal and/or injection of substantial quantities of water. It has been possible on several occasions to measure hydraulic responses at distant observation piezometers which can be correlated with these drilling and completion activities. Injection/withdrawal sequences and resulting hydraulic responses represent uncontrolled multiple borehole tests which, under appropriate conditions, are suitable for analysis of large-scale hydraulic parameters.

This mini-report presents a methodology for analyzing drilling responses to obtain large-scale (bulk) values of key hydraulic parameters. This analytical approach allows for immediate analysis of existing baseline monitoring data and can provide preliminary hydraulic parameter values until such a time that results from the proposed LHS tests are available. Results of the analysis described herein will provide values of key hydraulic parameters to be used as input for performance assessments conducted by Terra Therma.

2.0 OBJECTIVE

Availability of drilling response data from past activities at the BWIP Site can be analyzed to determine large-scale hydraulic parameters within the limitations discussed below. A well field simulator developed by Terra Therma provides a methodology to calculate large scale values of transmissivity and storativity for basalt interflows (aquifers) within the Columbia River Basalt. The well field simulator may be modified at some later date to incorporate leakage properties of basalt flow interiors (aquitards).

3.0 EVALUATION

3.1 OPERATIONAL APPROACH

Drilling and completion activities within the Hanford Reservation commonly involve injection and/or withdrawal of substantial volumes of water. Injection has typically been associated with fluid circulation losses during rotary drilling and withdrawals have occured during air drilling or well development. Since initiation of the BWIP Baseline Monitoring Program, water level responses in piezometers and observation wells have been correlated with many of these injection/withdrawal events. As an example, Figures 1A and 1B show the hydraulic response measured in observation piezometer DC-20C (Priest Rapids Member) resulting from injection and withdrawal of water into Wanapum Basalt during the drilling of borehole DC-23W. Because DC-20C is located 11,400 feet (Table 1) from DC-23W, Figures 1A and 1B indicate that drilling responses have had a large radius of influence within the Hanford Site. Table 1 summarizes drilling responses observed within the Hanford Site up to December, 1985. As shown, the maximum known distance of a drilling response was 32,000 feet (observed at DC-1 during the drilling of DC-20).

FIGURE 1. EXAMPLE OF HYDRAULIC RESPONSE CAUSED BY DRILLING/COMPLETION ACTIVITIES

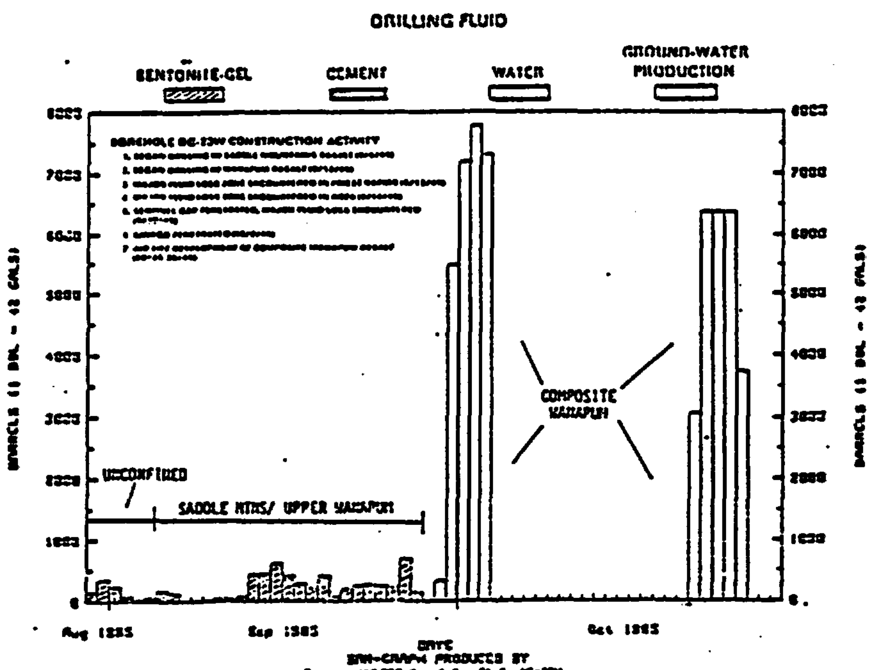


FIGURE 1A

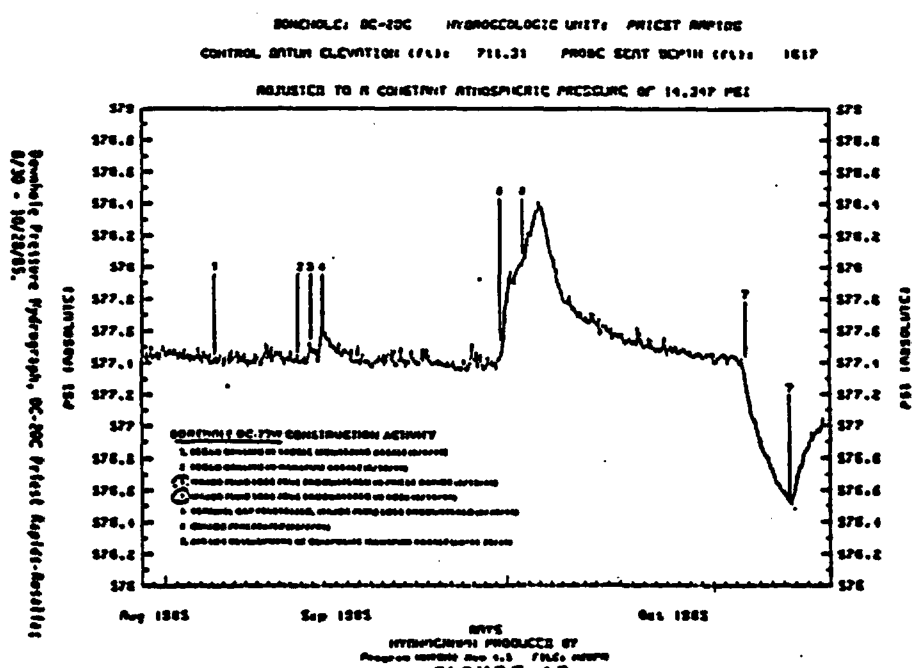


FIGURE 1B

TABLE 1. OBSERVED HYDROLOGIC RESPONSES DUE TO DRILLING/COMPLETION ACTIVITIES

ACTIVITY			OBSERVED CHANGES			
BOREHOLE NUMBER	ACTIVITY	ZONE OF FLUID LOSS OR GAIN	WELL INFLUENCED	DISTANCE * FROM ACTIVITY	UNIT AFFECTED	MAXIMUM AFFECT **
RRL-2C	DRILLING	UNCF/SM/WANP				
	DRILLING	GR 5 FLOW TOP				
RRL-2B	DRILLING	SAD MTS/WANAP				
	DRILLING	RC FLOW TOP	RRL-2A		RC FLOW TOP	2.3
	DRILLING	RC FLOW TOP	RRL-2C		RC FLOW TOP	69.3
RRL-14	BRID PLG REM	COMP GRD RONDE	DC-22C	2100	COHASSETT FT	3.8
	BRID PLG REM	COMP GRD RONDE	DC-22C	2100	UMTANUM FT	2.0
	BRID PLG REM	COMP GRD RONDE	DC-20C	13500	ROCKY COU FT	.8
	BRID PLG REM	COMP GRD RONDE	DC-20C	13500	COHASSETT FT	.7
	BRID PLG REM	COMP GRD RONDE	DC-20C	13500	UMTANUM FT	.5
RRL-17	DRILLING	COHAS FT/GR5 FT	RRL-2C	5300	COHASSETT FT	1.5
	DRILLING	COHAS FT/GR5 FT	DC-20C	4000	COHASSETT FT	1.0
DC-23W	DRILLING	UNCONFINED				
	DRILLING	PRIEST RAPIDS	DC-20C	11400	PRIEST RAPIDS	.2
	DRILLING	ROZA	DC-20C	11400	PRIEST RAPIDS	.5
	DRILLING	SENT GAP/GINK	DC-20C	11400	PRIEST RAPIDS	2.3
	AIR-LIFT DEV	COMPOSITE WANP	DC-20C	11400	PRIEST RAPIDS	-2.1
	DRILLING	SENT GAP/GINK	DC-22C	16600	PR RAP INTFLW	.9
	DRILLING	COMPOSITE WANP	DC-22C	16600	SENTINEL GAP	.8
	AIR-LIFT DEV	SENT GAP/GINK	DC-22C	16600	PR RAP INTFLW	-.9
	AIR-LIFT DEV	COMPOSITE WANP	DC-22C	16600	SENTINEL GAP	-1.0
DC-20C	AIR DRILLING	COMP WANP/GR	DC-1	32000	COMP WANP/GR	-3.0
	AIR DRILLING	PRIEST RAPIDS	DB-14	21700	PRIEST RAPIDS	-6.0
DC-19C	AIR DRILLING	PRIEST RAPIDS	DB-14	10000	PRIEST RAPIDS	-6.0
DC-22C	AIR DRILLING	PRIEST RAPIDS	DB-14	21700	PRIEST RAPIDS	-5.0
DC-19C/20C/22	AIR DRILLING	PRIEST RAPIDS	DC-16B	14000 - 16000	MABTON	-.9

* DISTANCES IN FEET, ESTIMATED FROM UNLABLED FIGURE (STRAIT, DECEMBER, 1985)
** ESTIMATED CHANGES IN FEET (ZEROS DO NOT INDICATE SIGNIFICANT FIGURES), NEGATIVE SIGN INDICATE WATER LEVEL DECLINES.

3.2 TECHNICAL APPROACH

Drilling and completion activities typically involve intermittent fluid injection or withdrawal at variable flow rates. Due to the uncontrolled nature of these activities, traditional pump test analyses, which commonly assume constant and continuous flow rates, are not generally applicable. To analyze drilling responses at BWIP, a variable flow rate analysis is used to predict hydraulic head changes at the point of interest, namely the observation borehole in which response was observed. Hydraulic parameter values are varied in a trial-and-error manner until the theoretical response best matches the measured field response. At this point, it is considered that the "calibrated" hydraulic parameter values used as input into the analytical model are similar to the actual in situ formation values.

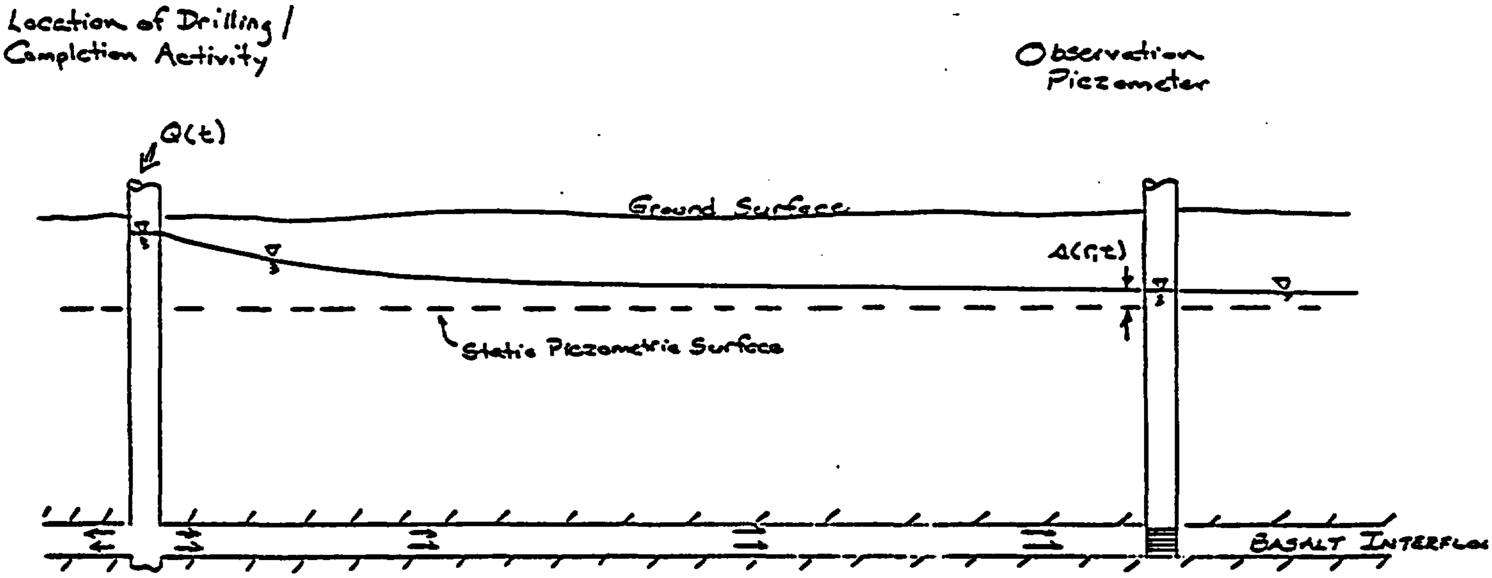
Sources of error may result from discrepancies between assumptions in the mathematical model and actual field conditions, inaccurate or incomplete field data, and hydraulic stresses from other sources which are not incorporated into the analysis. As a result, it may be difficult in some cases to exactly simulate the observed response, leaving a certain degree of uncertainty in the calibrated parameters. To assess this level of uncertainty, sensitivity studies are performed using ranges of the input parameters to determine upper bound, lower bound, and best guess values.

3.3 ASSUMPTIONS

For the case of an ideal confined aquifer, the physical system is shown in Figure 2. The following assumptions associated with the analysis of this system are as follows (Kruseman and de Ridder (1979), Davis and DeWiest (1966)):

1. The aquifer is seemingly infinite in areal extent.
2. The aquifer is homogeneous, isotropic, and of uniform thickness over the area influenced by drilling.
3. Prior to drilling activities, the piezometric surface is (nearly) horizontal over the area of influence.
4. The injection/withdrawal well penetrates the entire aquifer and fluid flow within the aquifer is horizontal.
5. Leakage into the aquifer from overlying or underlying aquitards is negligible.
6. The entire discharge must be provided by release of stored water and occurs instantaneously with decline in head.
7. The injection/withdrawal well diameter is infinitesimally small.

FIGURE 2. PHYSICAL SYSTEM OF AN IDEAL AQUIFER



Seldom are all of the above assumptions satisfied in nature. However, slight deviations are not prohibitive to the successful application of a confined aquifer analysis. In situations where deviations are more extreme, the above approach may still be usable for calculating upper or lower bound values of hydraulic parameters.

4.0 ANALYSIS

4.1 MATHEMATICAL FORMULATION

For the case of continuous fluid injection or withdrawal at a constant flow rate, the hydraulic response observed at a point is given by the following general equation (Theis, 1935):

(1) $$s(r,t) = \frac{Q}{(4\ pi\ T)} * W(u)$$

where:

(2) $$u = \frac{Sr^2}{(4Tt)}$$

s = hydraulic buildup (positive) or drawdown (negative)

Q = flow rate (positive for injection; negative for withdrawal)

pi = 3.14159

T = transmissivity

S = storativity

r = radial distance from the injection/withdrawal well

t = time since initiation of withdrawal/injection

and W(u) is the Theis (1935) dimensionless well function which incorporates major assumptions listed in Section 3.3.

Because well hydraulics solutions of the form given by equation (1) are based on linear governing equations, the effect of variable flow rates can be incorporated through the principal of superposition. If time varying flow rate is approximated as a step function, as shown in Figure 3, the resulting hydraulic response at the point of interest is given by (adapted from Roberts et al, 1982; Appendix 7):

(3) $$s(r,t) = \frac{Q_1}{(4\ pi\ T)}\ W(u_1) + \frac{1}{(4\ pi\ T)} \underset{n=2}{\overset{N}{SUM}}(Q_n - Q_{(n-1)})\ W(u_n)$$

where:

(4) $$u_n = \frac{Sr^2}{4\ T\ (t-t_n)}$$

N = total number of steps in flow rate step function

Q_n = flow rate during the nth step

t_n = time at beginning of the nth step

t = time of interest

and SUM represent a summation. For summation terms where t is less than t_n, the dimensionless buildup function is set equal to zero:

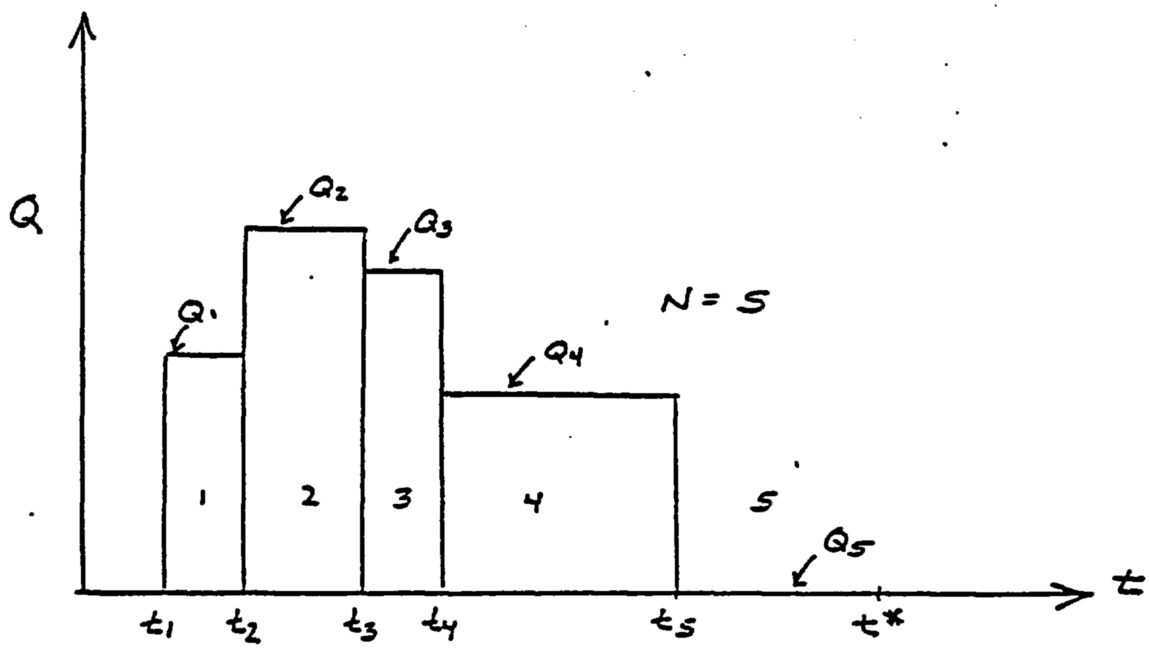
(5) if $t < t_n$; then $W(u) = 0$

To incorporate simple hydrologic boundaries, the principal of superposition is also utilized.

(6) Constant Head: $s(t) = s(r,t) - s(r_i,t)$

(7) Impermeable: $s(t) = s(r,t) + s(r_i,t)$

FIGURE 3. VARIABLE FLOW RATE STEP FUNCTION



where: r_i = image well distance

The image well is situated such that the boundary bisects and is normal to a line drawn between the real (injection/withdrawal) well and the image well. In the event that no boundary exists hydraulic response is given by:

(8) No Boundary: $s(t) = s(r,t)$

4.2 METHOD OF ANALYSIS

For a confined aquifer, independent hydraulic variables are aquifer transmissivity (T) and storativity (S). Formation values of the associated hydraulic parameters are determined by trial-and-error comparison between the theoretical and measured hydraulic response. To facilitate this process in an efficient manner, equations defining the analytical solution are evaluated using a computer program written for the IBM PC personal computer. The program has screen graphics to allow for visual superposition of theoretical response and measured field data (which are accessed from an external file).

The program prompts for fixed value input parameters including:

- o Flow rate - time (Q_n - t_n) values defining the variable flow rate step function.
- o Radial distance (r) to the observation point.

- Parameters defining the screen graphics.

- Boundary condition (no boundary, constant head, or impermeable) and image well distance.

Once the above parameters are entered, the user can iteratively enter different values of T and S, and observe an arithmetic line plot of buildup (s) versus time (t) predicted by the analytical method. In addition, field data (represented by points on the graphs) are superimposed upon the theoretical response. Hydraulic parameter values are varied until the theoretical line plot best coincides with the field data points. Once convergence is obtained, the calibrated values of T and S are considered similar to in situ formation properties. Because of the unknown boundary conditions on the Hanford Site, an impermeable or constant head boundary condition may be considered in the well simulation method to evaluate its effects.

4.3 RESULTS

Data from Figures 1A and 1B are utilized in this report to demonstrate the usefulness of analyzing existing baseline monitoring data to predict large scale hydraulic parameters. Tables 2 and 3 represent input values taken from Figure 1A and Figure 1B, respectively. Figure 1A shows the actual data used to develop the variable flow rate step function.

Performing the analysis described herein, "best guess" values of hydraulic parameters are as follows (Refer to Figure 4):

$$T = 3000 \text{ ft}^2/\text{day}$$

$$S = 2.5 * 10^{-5}$$

Sample data indicating sensitivity to changes in T and S are produced in Figures 5 and 6.

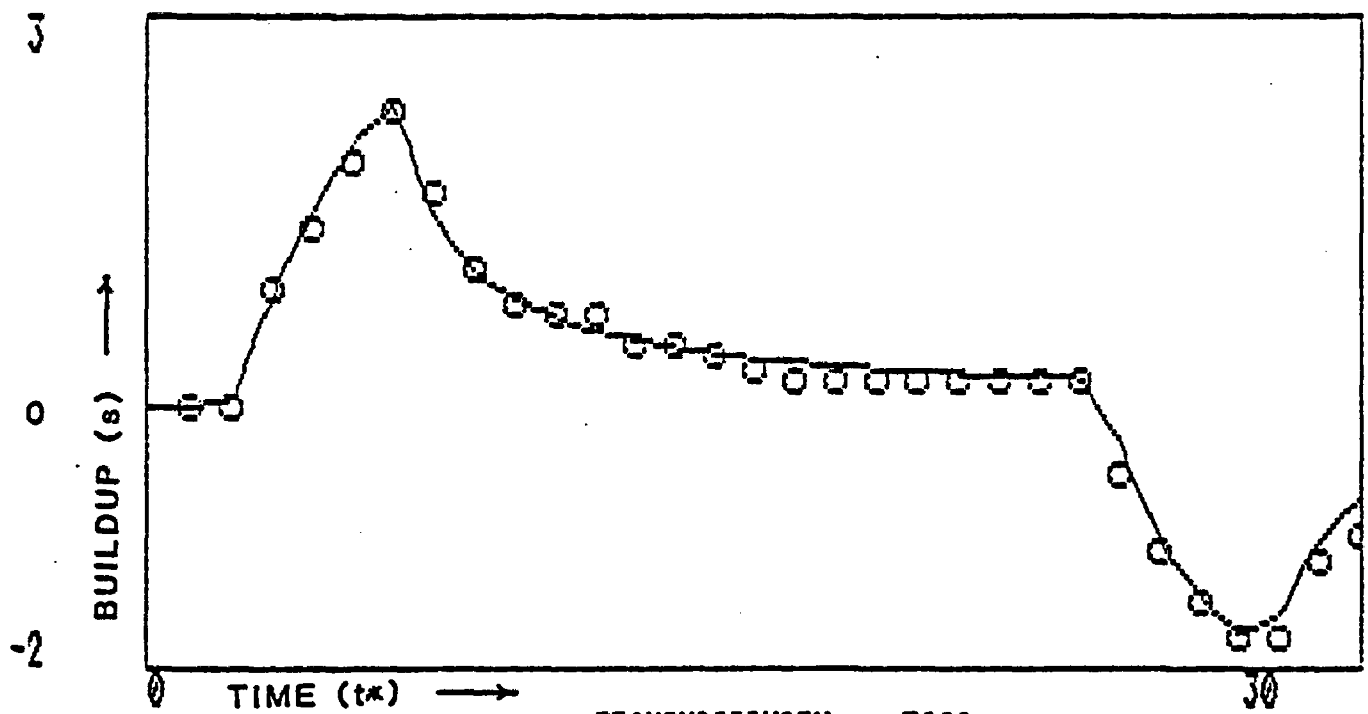
TABLE 2. FLOW RATE - TIME INPUT DATA

Date	Time (days)	Bbls	Time Period (days)	Q (cu.ft./d
September 29, 1985	1	367	1	2060
September 30, 1985	2	5483	1	30800
October 1, 1985	3	7183	1	40300
October 2, 1985	4	7793	1	43800
October 3, 1985	5	7300	1	41000
October 4, 1985	6	0	17	0
October 21, 1985	23	-3067	1	-17200
October 22, 1985	24	-6400	3	-35900
October 25, 1985	27	-3733	1	-21000
October 26, 1985	28	0	1	0

TABLE 3. HYDRAULIC HEAD FIELD DATA

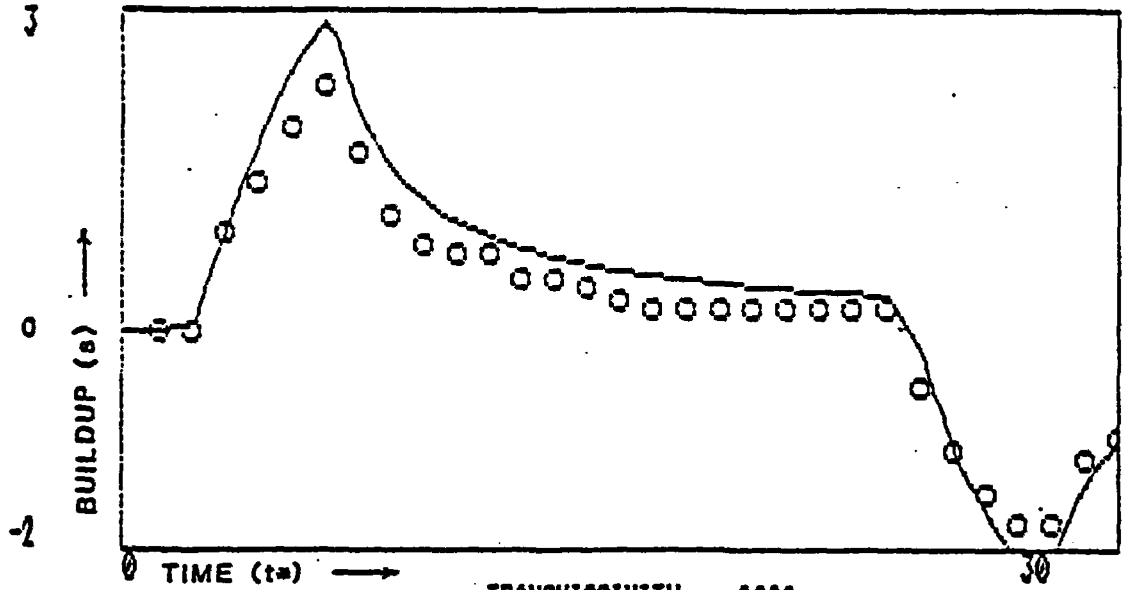
Date	Time (days)	PSI (abs)	Hydraulic Head (ft)	Buildup (ft)
September 29, 1985	1	577.38	1332.6	0
September 30, 1985	2	577.38	1332.6	0
October 1, 1985	3	577.77	1333.5	0.9
October 2, 1985	4	577.99	1334.0	1.4
October 3, 1985	5	578.21	1334.5	1.9
October 4, 1985	6	578.38	1334.9	2.3
October 5, 1985	7	578.12	1334.3	1.7
October 6, 1985	8	577.86	1333.7	1.1
October 7, 1985	9	577.73	1333.4	0.8
October 8, 1985	10	577.69	1333.3	0.7
October 9, 1985	11	577.69	1333.3	0.7
October 10, 1985	12	577.60	1333.1	0.5
October 11, 1985	13	577.60	1333.1	0.5
October 12, 1985	14	577.56	1333.0	0.4
October 13, 1985	15	577.51	1332.9	0.3
October 14, 1985	16	577.47	1332.8	0.2
October 15, 1985	17	577.47	1332.8	0.2
October 16, 1985	18	577.47	1332.8	0.2
October 17, 1985	19	577.47	1332.8	0.2
October 18, 1985	20	577.47	1332.8	0.2
October 19, 1985	21	577.47	1332.8	0.2
October 20, 1985	22	577.47	1332.8	0.2
October 21, 1985	23	577.47	1332.8	0.2
October 22, 1985	24	577.17	1332.1	-0.5
October 23, 1985	25	576.91	1331.5	-1.1
October 24, 1985	26	576.73	1331.1	-1.5
October 25, 1985	27	576.60	1330.8	-1.8
October 26, 1985	28	576.60	1330.8	-1.8
October 27, 1985	29	576.86	1331.4	-1.2
October 28, 1985	30	576.97	1331.6	-1

FIGURE 4. "BEST FIT" CURVE

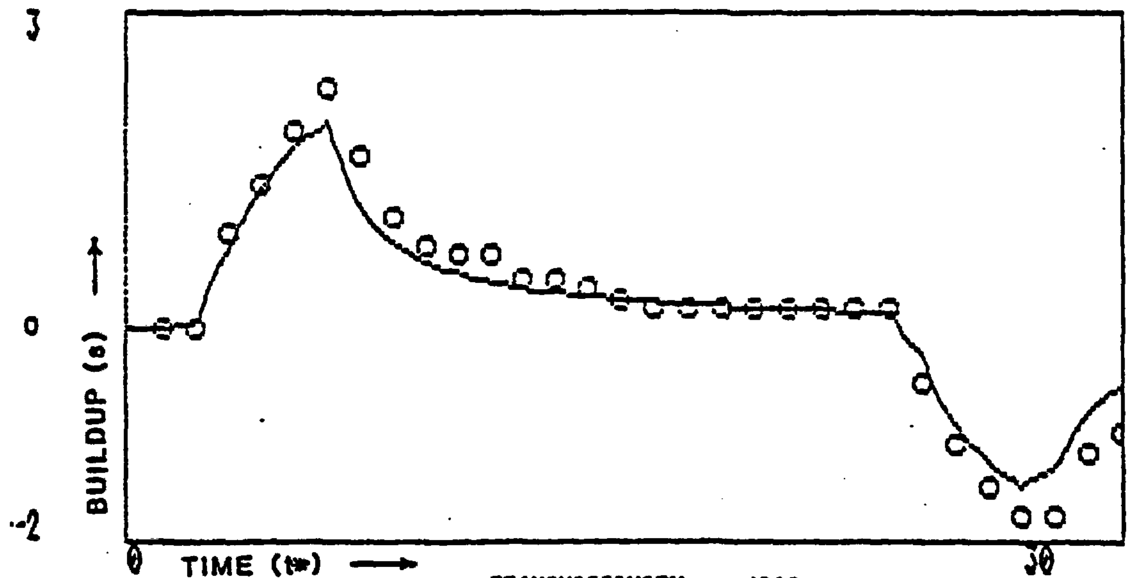


TRANSMISSIVITY = 3000
STORATIVITY = .000025
BOUNDARY CONDITION = 0
IMAGE WELL DISTANCE = 0

FIGURE 5. TRANSMISSIVITY SENSITIVITY CURVES

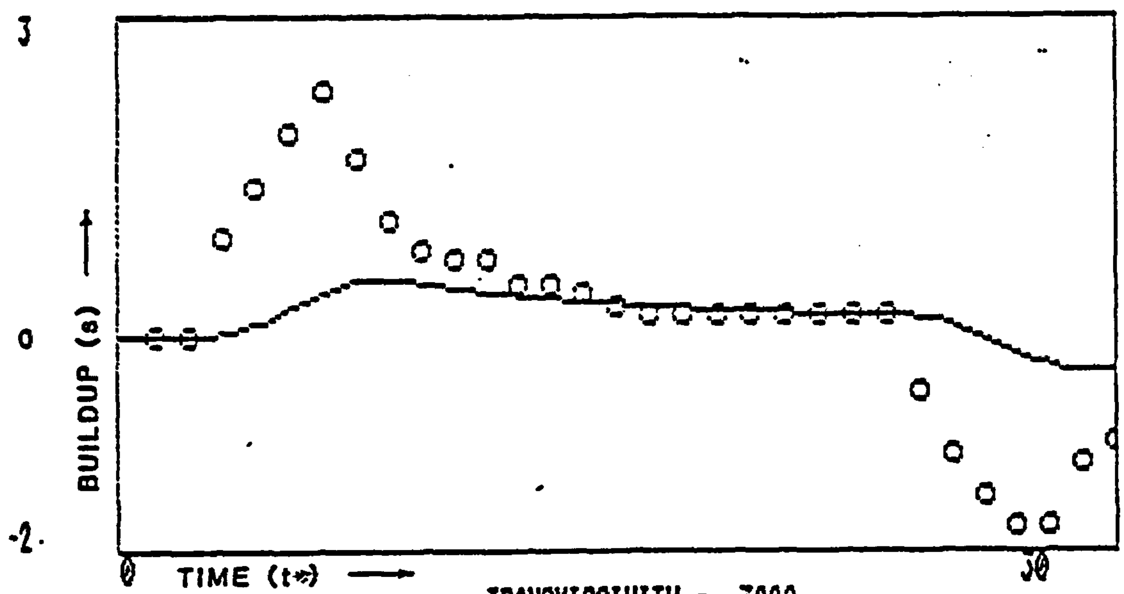


TRANSMISSIVITY = 2000
STORATIVITY = .000025
BOUNDARY CONDITION = 0
IMAGE WELL DISTANCE = 0

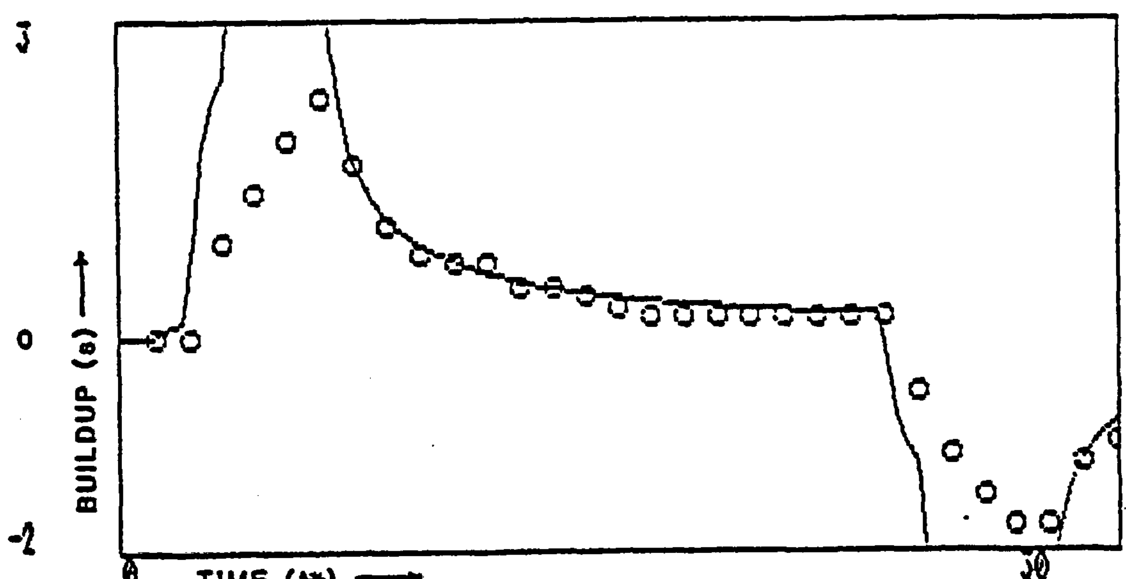


TRANSMISSIVITY = 4000
STORATIVITY = .000025
BOUNDARY CONDITION = 0
IMAGE WELL DISTANCE = 0

FIGURE 6. STORATIVITY SENSITIVITY CURVES



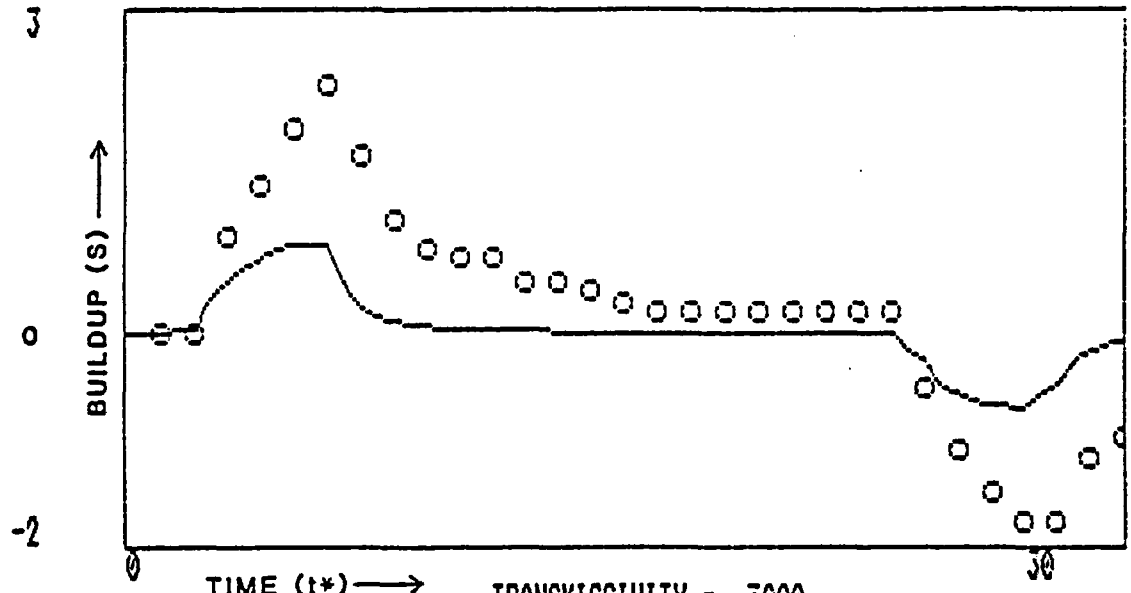
TRANSMISSIVITY = 3000
STORATIVITY = .00025
BOUNDARY CONDITION = 0
IMAGE WELL DISTANCE = 0



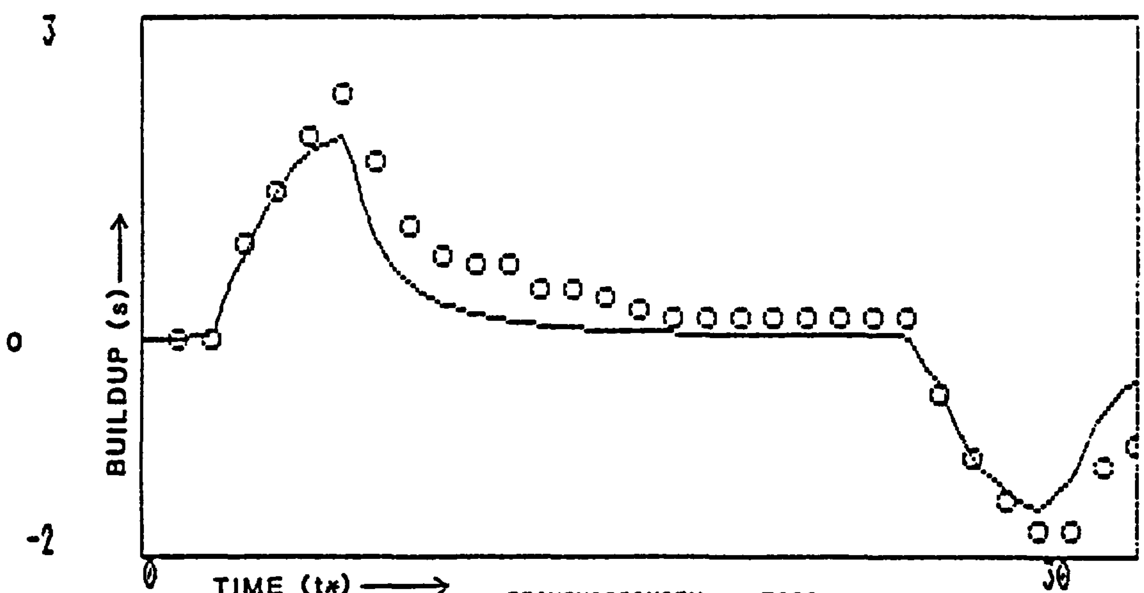
TRANSMISSIVITY = 3000
STORATIVITY = .0000025
BOUNDARY CONDITION = 0
IMAGE WELL DISTANCE = 0

For a constant head boundary condition, an image well distance of 90,000 feet (17 miles) will produce approximately the same curve. Therefore, a constant head boundary located within 8.5 miles of the injection/withdrawal well will alter the theoretical response whereas a boundary greater than 8.5 miles has little or no effect on the results (Figures 7 - 11). For an impermeable boundary condition, an image well distance greater than 150,000 feet (28 miles) produces negligible changes to the theoretical curve using the "best guess" T and S values. The same limitation as mentioned above for a constant head boundary is also true for an impermeable boundary, that is, an impermeable boundary of less than 14 miles will affect the theoretical response. No significant effects occur for an impermeable boundary greater than 14 miles (Figures 12 - 16).

FIGURES 7 - 8. CONSTANT HEAD BOUNDARY CURVES



TRANSMISSIVITY = 3000
STORATIVITY = .000025
BOUNDARY CONDITION = 1
IMAGE WELL DISTANCE = 17500



TRANSMISSIVITY = 3000
STORATIVITY = .000025
BOUNDARY CONDITION = 1
IMAGE WELL DISTANCE = 35000

FIGURE 8

FIGURES 9 - 10. CONSTANT HEAD BOUNDARY CURVES

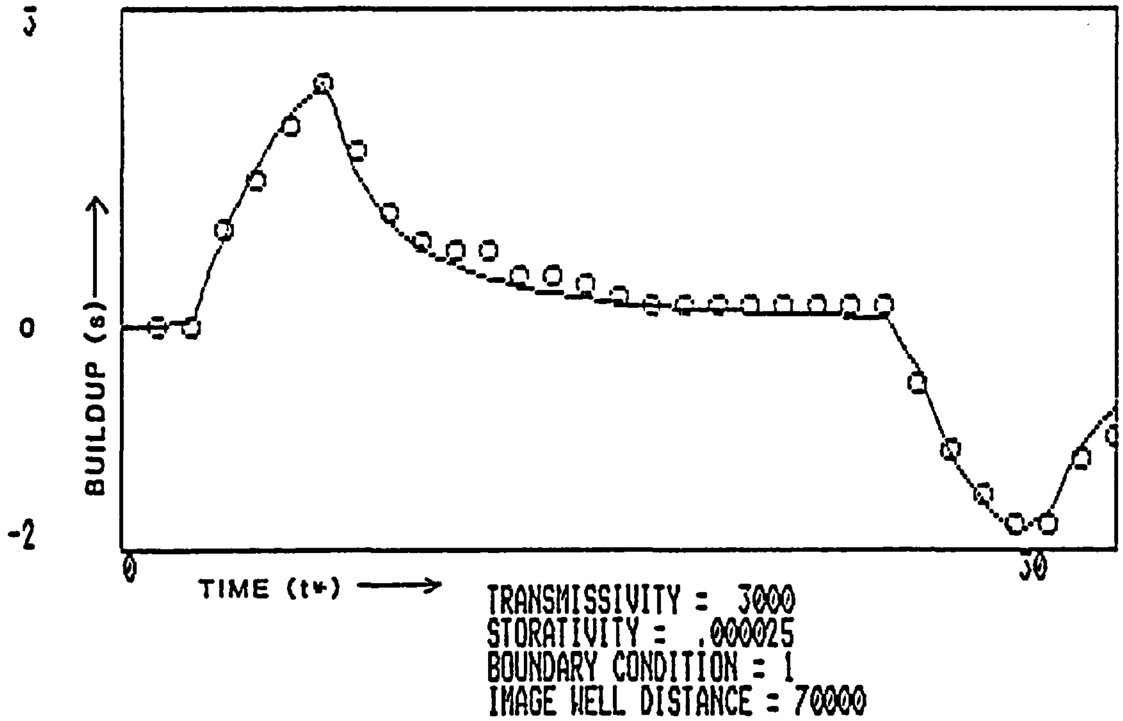


FIGURE 9

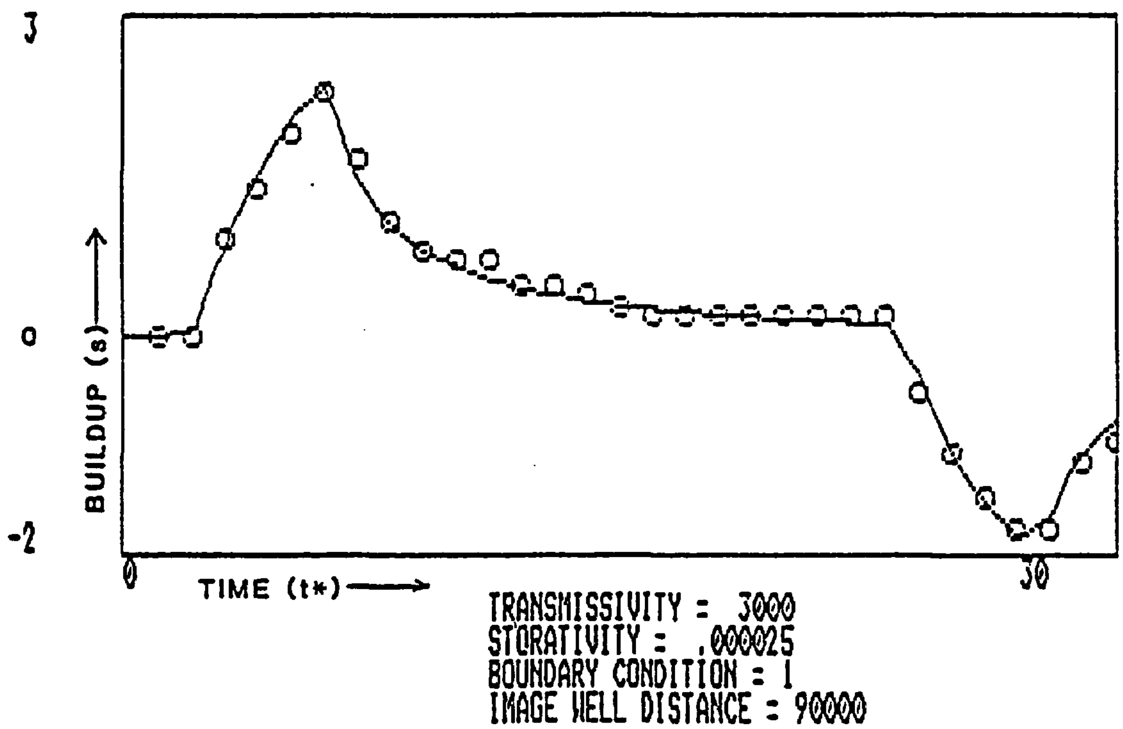
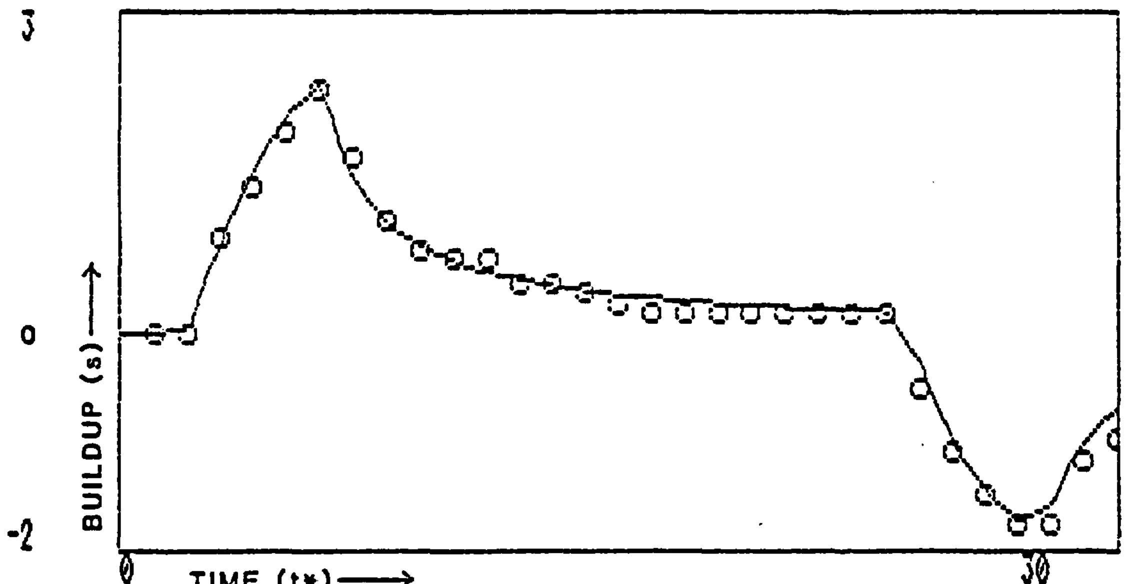


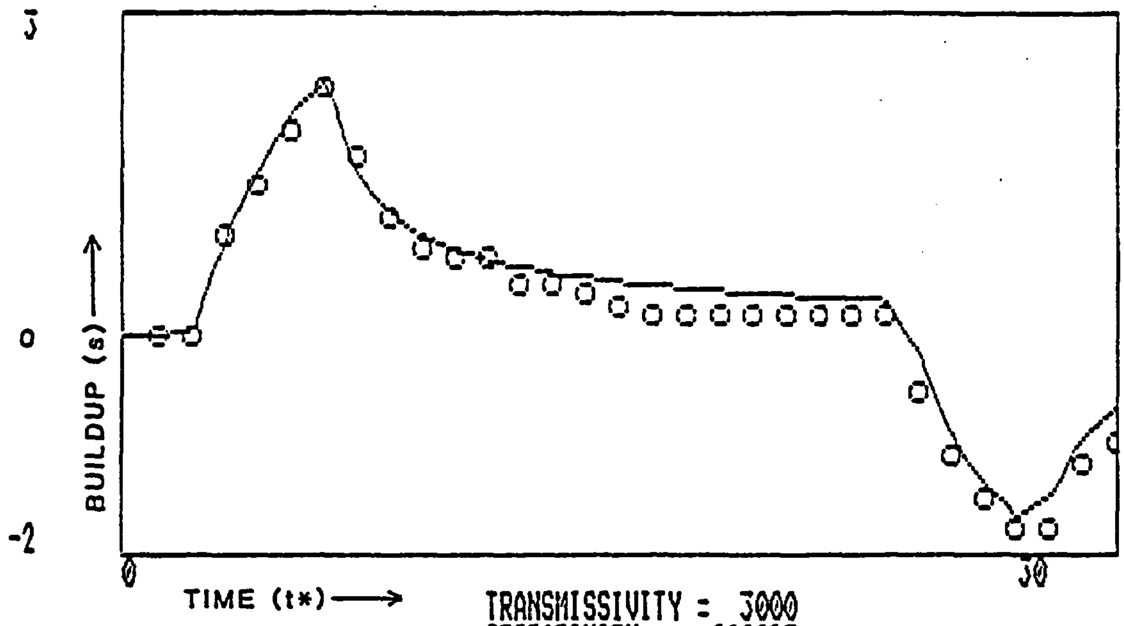
FIGURE 11. CONSTANT HEAD BOUNDARY CURVES



TRANSMISSIVITY = 3000
STORATIVITY = .000025
BOUNDARY CONDITION = 1
IMAGE WELL DISTANCE = 230000

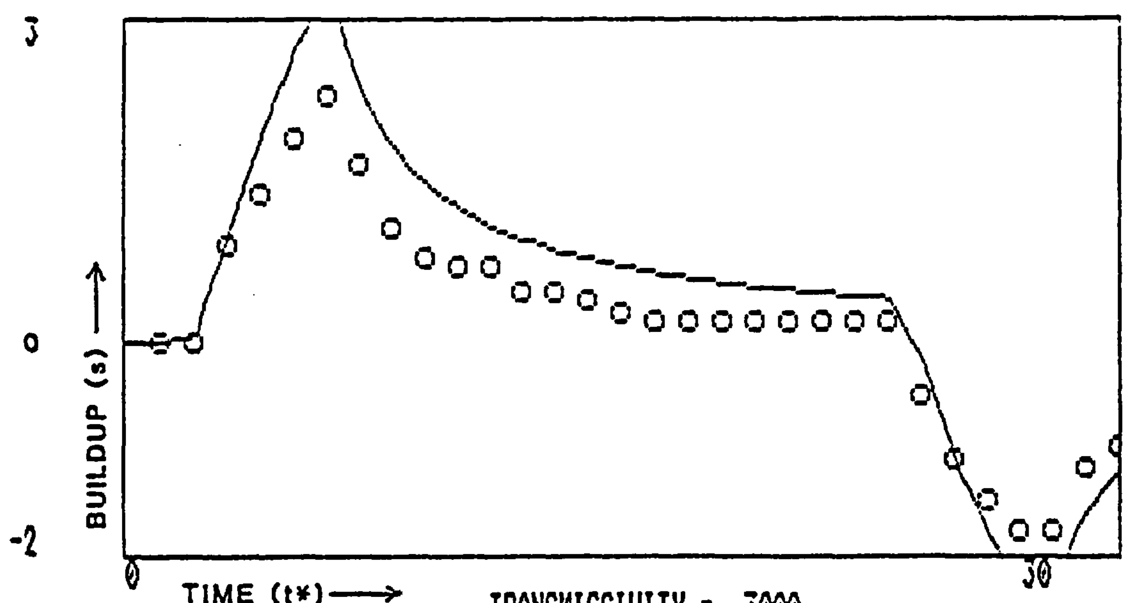
FIGURE 11

FIGURES 12 -13. IMPERMEABLE BOUNDARY CURVES



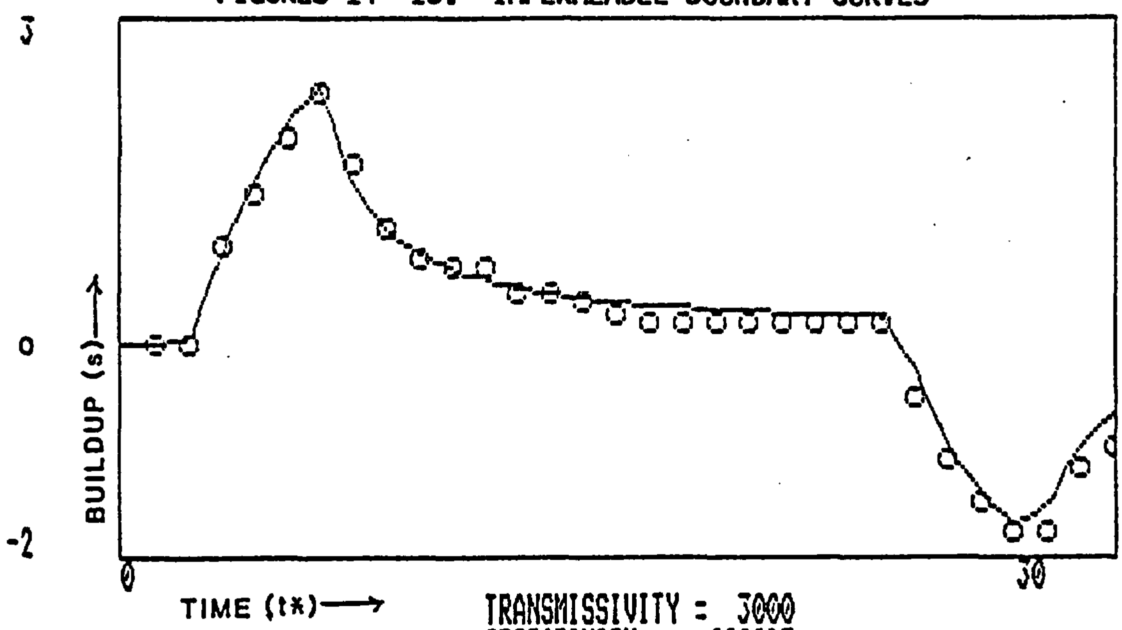
TRANSMISSIVITY = 3000
STORATIVITY = .000025
BOUNDARY CONDITION = 2
IMAGE WELL DISTANCE = 75000

FIGURE 13



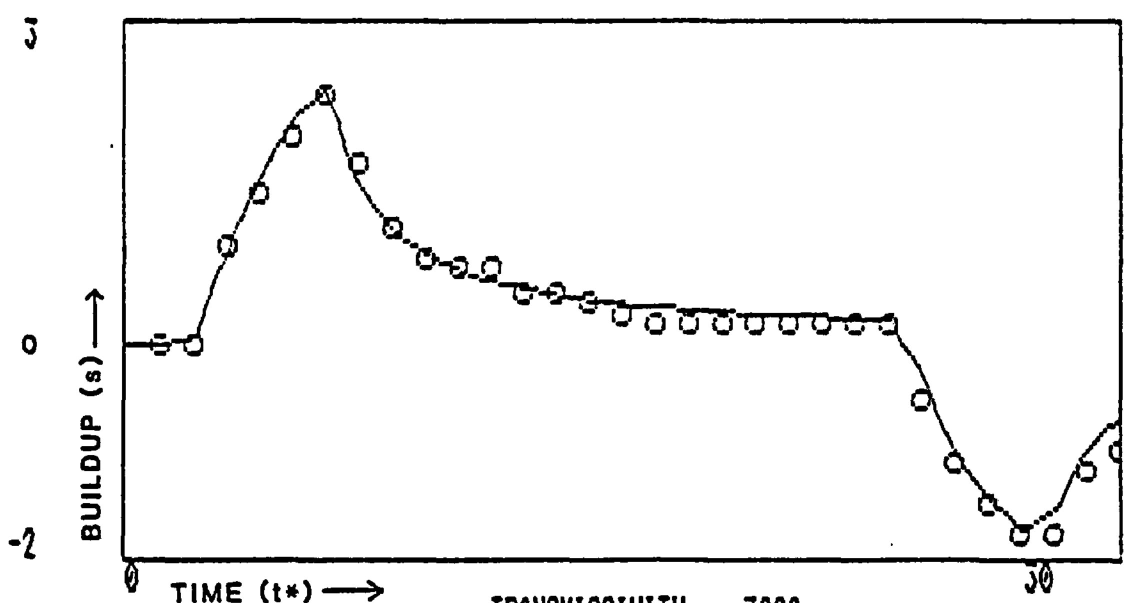
TRANSMISSIVITY = 3000
STORATIVITY = .000025
BOUNDARY CONDITION = 2
IMAGE WELL DISTANCE = 25000

FIGURES 14 -15. IMPERMEABLE BOUNDARY CURVES



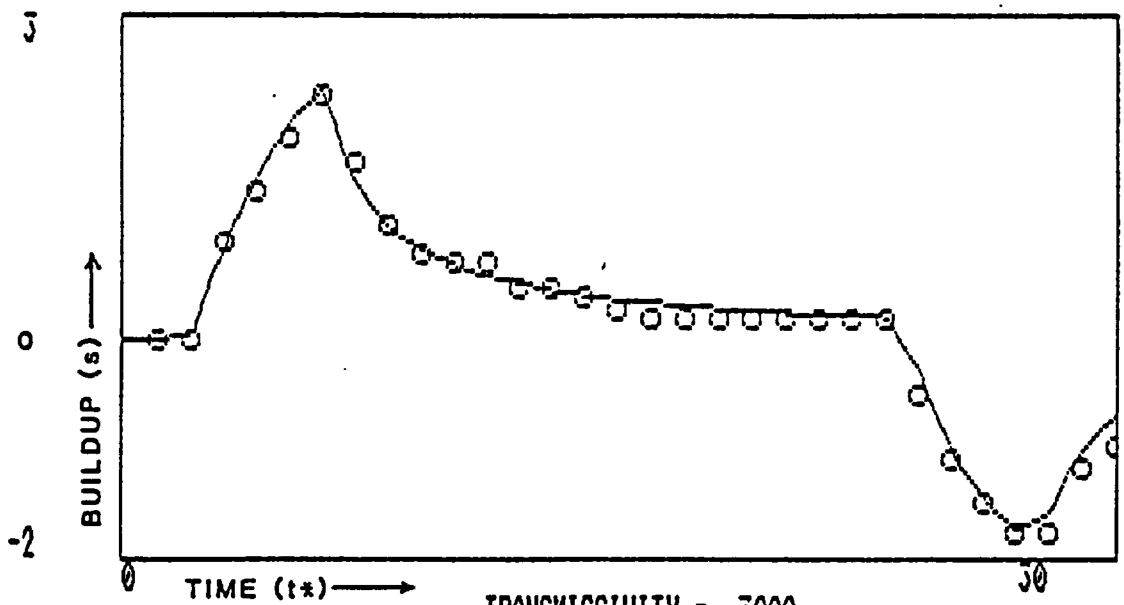
TRANSMISSIVITY = 3000
STORATIVITY = .000025
BOUNDARY CONDITION = 2
IMAGE WELL DISTANCE = 125000

FIGURE 14



TRANSMISSIVITY = 3000
STORATIVITY = .000025
BOUNDARY CONDITION = 2
IMAGE WELL DISTANCE = 150000

FIGURE 16. IMPERMEABLE BOUNDARY CURVES



TRANSMISSIVITY = 3000
STORATIVITY = .000025
BOUNDARY CONDITION = 2
IMAGE WELL DISTANCE = 250000

FIGURE 16

5.0 CONCLUSIONS

The analysis conducted for this report indicates a reliable method, within the limits of the aforementioned assumptions, in which to evaluate the existing data for large scale hydraulic parameters. Application of this analytical model will add to current knowledge of the Hanford Site. The results for T and S obtained above using the data from boreholes DC-20C and DC-23W is on the order of expected values.

Although this model will generally be used to analyze an infinite medium, it will be useful to see what effects, if any, can be expected with placement of either a constant head boundary or an impermeable boundary in the ground water flow system. For the case analyzed, image well distances of greater than 17 and 28 miles for a constant head or impermeable boundary, respectively, would have a negligible impact on the theoretical response predicted by the analytical model. It is concluded that boundaries located beyond these distances could not be identified by the analysis described herein.

6.0 DISCUSSION

Responses similar in magnitude to those measured in DC-20C and DC-23W have also been measured in DC-19C, DC-20C, DC-22C, RRL-2A, RRL-2C piezometers during the drilling and/or completion of RRL-2B, RRL-14, RRL-17, and DC-23W. This data can be readily used to conduct the same type of analysis. It may also be possible to analyze responses in DC-1 piezometers during the drilling of DC-20C. This latter analysis may be particularly interesting because of the relatively large distance involved (on the order of 6 miles). Terra Therma is continuing its study of the available data.

Further analysis of boundary conditions, incorporation of equations to account for leakage from adjacent aquifers, and comparison with single borehole data will be included in the update of this mini-report.

7.0 REFERENCES

Davis, S.N. and R.J.M. DeWiest. 1966. Hydrogeology. John Wiley & Sons.

Kruseman, G.P. and N.A. de Ridder. 1979. Analysis and Evaluation of Pumping Test Data. International Institute for Land Reclamation and Improvement, Bulletin 11, Wageningen, The Netherlands.

Roberts W., et al. 1982. In Situ Test Programs Related to Design and Construction of High-Level Nuclear Waste (HLW) Deep Geologic Repositories. Prepared by Golder Associates for the US NRC. NUREG/CR-3056.

Theis, C.V. 1935. The Relation Between Lowering of the Piezometric Surface and the Rate and Duration of Discharge of a Well Using Groundwater Storage. Trans. Amer. Geophys. Union, vol 16, pp. 519-524.