COLLECTION AND ANALYSIS
OF PUMP TEST DATA
FOR TRANSMISSIVITY VALUES

K. L. Kipp and R. D. Mudd

Battelle

Pacific Northwest Laboratories
Richland, Washington 99352

1973

Prepared for the U.S. Atomic Energy
Commission under Contract AT(45-1):1830

NOTICE

The report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
U.S. ATOMIC ENERGY COMMISSION
Under Contract AT(45-1)-1830

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy \$5.45; Microfiche \$1.45

3 3679 00046 5197

BNWL-1709

COLLECTION AND ANALYSIS OF
PUMP TEST DATA FOR TRANSMISSIVITY VALUES

by

K. L. Kipp
R. D. Mudd

Water and Land Resources Department

1973

This report is based on work sponsored by the
Atlantic Richfield Hanford Company under United
States Atomic Energy Commission Contract AT(45-1)-2130

BATTELLE
PACIFIC NORTHWEST LABORATORIES
RICHLAND, WASHINGTON 99352

SUMMARY

This report describes the analysis of the well pump tests performed in 1969 to determine the field measured transmissivity values used in "The Transmissivity Iterative Calculation Routine - Theory and Numerical Implementation," BNWL-1706. Previously accumulated pump test transmissivity values which were also used as input data are included for completeness and the analytical models employed for pump test analyses are described. A sensitivity study was performed on the pertinent variables and procedures of the pump test analyses. Tables of transmissivity results and the graphs used to obtain them are included. Unfortunately, meaningful values for the storage coefficient were unobtainable.

CONTENTS

	<u>Page</u>
SUMMARY.	i
SYMBOLS AND DIMENSIONS	iv
INTRODUCTION	1
DETERMINATION OF AQUIFER PROPERTIES BY WELL PUMP TESTS	3
THE ANALYTICAL MODELS FOR PUMPED WELLS	4
Boulton Model for Totally Penetrating Wells in Unconfined Aquifers.	4
Dagan Model for Partially-Penetrating Wells in Unconfined Aquifers.	5
Theis Model for Wells Totally Penetrating Confined Aquifers	7
SENSITIVITY OF THE ANALYSES OF THE 1969 PUMP TESTS	8
The Effect of Casing Resistance to Flow	8
The Effect of Data from Observation Wells	9
The Effect of the Selected Flow Model	10
METHOD OF DATA ANALYSIS.	10
SUMMARY OF RESULTS	12
CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK.	14
ACKNOWLEDGMENTS.	17
REFERENCES	19
APPENDIX A - TYPE CURVES AND DATA PLOTS USED TO ANALYZE THE 1969 PUMP TESTS.	A-1

SYMBOLS AND DIMENSIONS

r_w	well radius	(ft)
h_e	initial aquifer saturated thickness	(ft)
J_0	Bessel function	
K	hydraulic conductivity	(ft/min)
s	drawdown in the pumped well	(ft)
σ	storage coefficient	
T	transmissivity ($= K h_e$)	(ft ² /min)
Q	volumetric flow rate	(ft ³ /min)
t	time	(min)

COLLECTION AND ANALYSIS OF
PUMP TEST DATA FOR TRANSMISSIVITY VALUES

INTRODUCTION

The values used for calculating the Hanford transmissivity distribution were obtained from pump tests at selected wells, one group of which were performed in 1969 by personnel of Battelle's Water and Land Resources Department. Other tests had been performed previously. The 1969 tests were analyzed in conjunction with the VTT model development, whereas those performed before that date were reported by Bierschenk.^{1,2}

At various times techniques other than pump testing for transmissivity determinations have been tried at Hanford on an experimental basis; values thus obtained have been summarized by Bierschenk.¹ In addition, many estimates of transmissivity have been made using specific capacity data. Some of these values were used in areas where pump tests were not complete.

This report analyzes the group of pump tests performed in 1969. The previously accumulated transmissivity data is included for completeness, and results for the four wells tested in both groups are compared.

DETERMINATION OF AQUIFER PROPERTIES BY WELL PUMP TESTS

The literature contains a significant amount of material on the mathematical models used for the analysis of well pump tests and instructions for use of the models. A good summary is found in Lohman.³ Stallman⁴ presented a valuable discussion on aspects of analyses of pump tests in unconfined aquifers. This report will be restricted to discussion of the models used to analyze the pump tests performed on the Hanford Reservation in 1969.

There are several procedures for testing a well to determine aquifer parameters. All involve the following steps.

- An idealized flow pattern is assumed--confined or unconfined, totally or partially penetrating well, leaky or impermeable boundaries, isotropic or anisotropic permeability, etc.
- A relationship for the free surface profile or the piezometric head in the well is derived from a mathematical model under the conditions of the pumping test--constant head, constant discharge, drawdown, recovery, slug injection, periodic pumping, etc.
- The test is performed. The discharge flow rate and head in the pumped well are measured. A nearby observation well, if available, can be used to measure the free surface profile in an unconfined aquifer or the hydraulic potential in a confined aquifer.
- These measured values are compared with the theoretical prediction curves of the model selected. Model parameters containing the hydraulic conductivity (permeability) and the effective porosity or storage coefficient are calculated. In general, it is more difficult to determine the storage coefficient accurately in unconfined aquifers due to delayed yield effects.

The aquifer parameters determined from a pumping test are indicators for the particular aquifer zone that the pump test affects. Idealization and lack of knowledge causes inhomogeneities, unknown boundaries, anisotropic permeability effects and unknown leakage to be averaged into the measured hydraulic conductivity. Several factors may reduce the accuracy of the aquifer parameters determined through pump tests, including:

- 1) excessive heterogeneity of the aquifer or the presence of unknown boundaries;

- 2) thinning of the saturated zone when using the Theis model in an unconfined flow situation;
- 3) a storage coefficient value that varies in time due to delayed yield effects;⁵
- 4) significant observation well response lags;⁴
- 5) excessive variation in the pump discharge flow rate when it is assumed to be steady in the analytical model; and
- 6) pumping rates that are too high so that casing resistance to flow becomes significant or drawdown becomes a large fraction of the initial aquifer thickness.

These factors must be kept in mind when analyzing pump test data. Since the Variable Thickness Transient Model for the Hanford Reservation simulates groundwater flow in unconfined or free-surface aquifers, one would expect that analytical models for unconfined pump tests, which include the significant vertical flow near the pumped well, should apply to the pump test data taken on the Hanford Reservation.

THE ANALYTICAL MODELS FOR PUMPED WELLS

The following models for unconfined aquifers were used.

The Boulton Model for Totally Penetrating Wells in Unconfined Aquifers

The solution for this case was derived by Boulton³ as

$$s = \frac{Q}{2\pi T} \int_0^{\infty} \frac{J_0(\lambda r_w')}{\lambda} \left[1 - \text{Sech} \lambda e^{-\lambda \tau} \tanh \lambda \right] d\lambda$$

$$r_w' = \frac{r_w}{h_e}, \quad \tau = \frac{Kt}{\sigma h_e} \quad (1)$$

This equation for the drawdown applies to a given radius and time. Since most of the available data for this study were from drawdown measurements in the pumped well, the expression shown evaluates the drawdown at the radius of the pumped well. The hydraulic potential is averaged over the entire aquifer thickness. Other assumptions include:

- 1) small total drawdowns relative to the initial saturated thickness;

- 2) screening or perforation of the well over the entire aquifer thickness;
- 3) isotropic, homogeneous permeability within the zone of well influence during the pump test;
- 4) an impervious aquifer bottom and effectively infinite lateral aquifer extent during the pump test;
- 5) no recharge boundaries;
- 6) a steady pump discharge flow rate;
- 7) lack of significant delayed yield effects; and
- 8) neglect of turbulent head loss through the well casing or screen.

The pumped well is modeled mathematically by a line sink of constant discharge per unit length. The free surface boundary condition has been linearized about its initial horizontal position.

The solution requires that a separate type-curve be computed for each well analyzed since the dimensionless well radius depends on the initial aquifer thickness. Equation 1 gives the drawdown in the well during the pumping period. Superpositioning can be used to model the recovery period, yielding the following equation

$$s = \frac{Q}{2\pi T} \int_0^{\infty} \frac{J_0(\lambda r'_w)}{\lambda} \operatorname{sech} \lambda \left[e^{-\lambda(\tau - \tau_s \hat{s}) \tanh \lambda} - e^{-\lambda \tau \tanh \lambda} \right] d\lambda$$

where $\tau_s = \frac{K t_s}{\sigma h_e}$

$t_s = \text{pump stop time} \quad (2)$

Note that this equation is a function of an additional parameter τ_s , which is the dimensionless time the pumping was stopped. A trial and error search for the proper τ_s value is necessary to analyze a recovery test period since K and J are unknowns.

The Dagan Model for Partially-Penetrating Wells in Unconfined Aquifers

Figure 1 illustrates the situation for which Dagan⁶ derived a solution. The expression for the drawdown at the radius of the pumped well is

$$\begin{aligned}
s = \frac{Q}{2\pi T} & \left[\frac{1}{L'} \frac{1}{2} \ln \left(\frac{\sqrt{r_w'^2 + L_1'^2} + L_1'}{r_w'} \cdot \frac{\sqrt{r_w'^2 + (L_1' + L_2')^2} - L_1' - L_2'}{\sqrt{r_w'^2 + L_2'^2} - 2L_2'} \right) \right. \\
& - \frac{1}{L'} \int_0^\infty \frac{\cosh \lambda (1 - L_2')}{\lambda \sinh \lambda \cosh \lambda} e^{-\lambda r} \tanh \lambda J_0(\lambda r_w') \left(\sinh \left(\lambda (1 - L_1') \right) \right) \\
& - \sinh \left(\lambda (1 - L_2') \right) d\lambda \\
& \left. + \frac{1}{L'} \int_0^\infty \frac{\cosh L_1'}{\lambda \sinh \lambda} J_0(\lambda r_w') e^{-\lambda r} \left[\sinh(\lambda L_2') - \sinh(\lambda L_1') \right] d\lambda \right]
\end{aligned} \tag{3}$$

where $L' = \frac{L}{h_e}$; $r_w' = \frac{r_w}{h_e}$; $L_1' = \frac{L_1}{h_e}$; $L_2' = \frac{L_2}{h_e}$

L_1, L_2, L_3 as shown in Figure 1.

FIGURE 1. A Partially Penetrating Well in an Unconfined Aquifer

The assumptions made for the Boulton solution apply to the Dagan solution also, except in this case the well only partially penetrates the aquifer.

Equation 3 gives the drawdown as a function of time and well radius for a given fraction of penetration L_2/h_e . In addition, the top of the line sink can be made to correspond to the top of the perforations when they end below the free surface level. The drawdown in the pumped well is taken to be the potential at the bottom of the well at the well radius. This approximation is necessary because the well is modeled by a line sink and vertical flow is included in the model. Again superpositioning gives Equation 4 for the recovery period of a pump test.

$$s = \frac{Q}{2T} \int_0^\infty \frac{1}{L} \frac{J_0(\lambda r_w') \cosh \lambda (1+L_1')}{\lambda \sinh \lambda \cosh \lambda} \left(\sinh \lambda (1-L_1') - \sinh \lambda (1-L_2') \right) \left(e^{-\lambda (\tau - \tau_s)} \tanh \lambda - e^{-\lambda \tau} \tanh \lambda \right) d\lambda \quad (4)$$

The dimensionless pump stop time τ_s also appears here as in Equation 2.

The Theis Model for Wells Totally Penetrating Confined Aquifers

Theis⁷ presented the first transient solution for pump test analyses. Although it is strictly applicable to totally penetrating wells in confined aquifers, it has been overworked by its application to many other situations of unconfined and partial penetration because of its simplicity. Bierschenk used the Theis model for all of the pump tests he analyzed. The Theis solution is given by Equation 5 for the pumping period.

$$s = \frac{Q}{4\pi T} \int_{\frac{r_w}{2S}}^\infty \frac{e^{-\lambda}}{\lambda} d\lambda \quad (5)$$

where S = storage coefficient

Again the same assumptions apply as for the Boulton model with the addition of an impermeable boundary above the aquifer. Superpositioning gives the expression for the recovery period in Equation 6:

$$s = \frac{Q}{4\pi T} \int_{\frac{r_w^2 S}{4Tt}}^{\frac{r_w^2 S}{4T(t-t_s)}} \frac{e^{-\lambda}}{\lambda} d\lambda \quad (6)$$

where t_s = pump stop time.

Lohman³ gives examples of applications of these and other models of pumped well behavior. This solution is applicable to totally penetrating pumped wells in locally confined areas of the Hanford water table aquifer.

All of the above solutions model the well by a line sink and thus cannot represent potential distributions within or very close to the pumped well. Therefore, the drawdown within the wellbore must be approximated. In each of the above solutions the drawdown at the radius of the well casing was taken to represent the drawdown within the well.

Hantush⁸ has derived a model for partially penetrating wells in confined aquifers. He has also extensively treated pumped wells in aquifers with leaky boundaries.^{9,10,11,12} Time did not permit investigation of the applicability of these other solutions.

SENSITIVITY OF THE ANALYSES OF THE 1969 PUMP TESTS

Several analyses were performed to determine the sensitivity of this work to some of the factors listed above.

The Effect of Casing Resistance to Flow

The results of step-drawdown tests performed on several wells indicate that casing turbulent head loss (casing resistance) is significant in most of the tests. Although mathematical models do not account for this head loss, a step-drawdown test can be used to estimate it, assuming that the head loss S_L is proportional to the square of the flowrate Q :

$$S_L \propto CQ^2$$

Step-drawdown tests can be used to obtain C. As shown by Bierschenk,¹ C varies for each well, depending on its perforation pattern, casing condition, and the formation condition just outside the casing. Wells 679-61-66,-71-77 and 3099-49-E16 were step-drawdown tested in 1969. Well 699-2-3 was step-drawdown tested in 1958. The head loss due to casing resistance at the average flow rate was subtracted from the measured head loss and the transmissivity and storage coefficient determined. The results are summarized in Table 1.

TABLE 1. TRANSMISSIVITY AND STORAGE COEFFICIENT DATA
SUMMARY FROM STEP DRAWDOWN TESTS

<u>Well Number</u>	<u>Head Loss Caused by Casing Resistance at the Average Pump Flowrate (Feet)</u>	<u>Effect on the Trans- missivity and Storage Coefficient</u>
3099-49-E16	0.1 out of 0.5 maximum drawdown	T increased 10% σ increased 200%
699-2-3	3.7 out of 5.6	T increased 400% agrees with re- covery data σ decreased 90%
699-61-66	0.1 out of 1	Negligible change
699-71-77	0.5 out of 1.9	T increased 30% σ increased 100%

The conclusion is that the significance of casing resistance for a given pump test flow rate should be considered individually for each well. The drawdown and recovery measurements in the pumped well contain whatever effect this resistance has on that well. The recovery data in the later stages of the recovery period are essentially unaffected by casing resistance because flow rates are low. Bierschenk¹ arrived at similar conclusions.

The Effect of Data from Observation Wells

Two observation wells were available from which drawdown and recovery data were collected for wells 699-36-61 and 699-43-89. Results from these wells agreed with the recovery trans-

missivities of the pumped well and gave more reasonable values for the storage coefficient. However, the drawdown tests showed a 50% difference in transmissivity, with the observation well for 699-36-61 yielding higher results and that for 699-43-89 yielding lower results than their respective pumped wells. In general, observation wells give better data than pumped wells.

The Effect of the Selected Flow Model

One well, 699-71-77, was analyzed under two assumed aquifer thicknesses. In one analysis the well was assumed to totally penetrate an aquifer of 190 feet; in the other it was assumed to partially penetrate an aquifer of 367 feet. The result was a computed increase in the hydraulic conductivity of about 50% from the totally penetrating to the partially penetrating analysis. A Theis analysis gave a hydraulic conductivity of four times the Boulton analysis value. The storage coefficient values showed variations of two orders of magnitude. Therefore, it is evident that the selection of the mathematical model greatly affects the values obtained for the aquifer parameters. This conclusion cannot be overemphasized. A reanalysis of the four well tests presented in Table 1 using the Boulton or Dagan model in comparison to Bierschenk's^{1,2} Theis analysis shows differences of as much as a factor of ten in the transmissivity values. This further illustrates the sensitivity of the aquifer parameters to the analytical model selected.

In the course of this work the effects of recharge or impermeable boundaries were neglected, although the former are known to be present in wells in the vicinity of the Columbia River. Furthermore, the effects of a recharge boundary, a semi-pervious adjacent aquifer, a significantly sloping water-table aquifer, or an aquifer of non-uniform thickness on the drawdown data are difficult to distinguish from those of partial penetration of the pumped well.^{10,11,12,14,15,16} Additional geological information about the local flow system boundaries is needed to give the interpretation of the observed drawdown data.

METHODS OF DATA ANALYSIS

The appropriate analytical model and its geometric parameters were selected for each tested well by using the driller's log, geological cross section, and drill sample information. Clay content analyses were made for selected drill samples in order to help indicate locally confined areas and the aquifer bottom. A clay and silt content greater than about 40% was considered

impermeable, although relative changes from permeable sands to slightly permeable sandy clays can be significant. Clay lenses separating sections of the aquifer were located in this manner.

Once the geometrical parameters were determined and the model selected, theoretical curves were generated for analysis of the pump test data.

Equations 1, 3 or 5 are of the form

$$s = \frac{Q}{2\pi T} W_i(\tau) \quad i = B, D \text{ for models A, B} \quad (7a)$$

$$\text{where } \tau = \frac{Kt}{\sigma h_e} \quad (7b)$$

so

$$\log s = \log \frac{Q}{2\pi T} + \log W_i(\tau)$$

and

$$\log t = \log \frac{\sigma h_e}{K} + \log \tau$$

Thus on a log-log scale there is a direct relation between s and W_i and t and τ within an additive constant.

Therefore, log-log plots of drawdown versus time for the measured data and the analytical drawdown curve were overlaid and the position for a best fit was selected, keeping axes parallel. A match point was chosen and the aquifer parameters were calculated from Equations 7a and 7b.

Similar equations apply to the analysis of the recovery phase of the pump test. However, as shown in Equations 2, 4, and 6, an additional parameter is involved. Therefore the same technique is used but a set of analytical curves for various values of τ_s must be generated. The best curve and the best position along that curve are selected for the data matching and aquifer parameter calculations. It should be noted that for the Theis model an approximation to the integral allows the variables containing t and t_s to be combined into a single variable, thus avoiding the multiple curve search procedure required for this analysis.³

Due to the vertical flow effects present near unconfined pumped wells there is a potential difference in the theoretical models between the bottom and the top of the well at the radius of the well casing. The most realistic approximation to the drawdown in the actual well of finite radius is

the average of the potential at the well radius over the screened or perforated length of casing. For the Boulton model this average must be taken over the saturated thickness of the aquifer. For the Dagan model the increase in accuracy did not justify the effort necessary to carry out this computation for the general case. Therefore the potential at the bottom of the well (L2 in Figure 1) was selected to represent the drawdown in the pumped well. Curves were also calculated on the basis of the potential at the top of the well just outside the well casing. The data for some of the tests appeared to better match this alternate drawdown potential. These analytical difficulties do not occur when observation wells are used.

SUMMARY OF RESULTS

Appendix A contains the graphs of the data and analytical curves used for the analysis of the 1969 pump tests. The match points used to link the dimensional data plots with the dimensionless type curves are indicated by $\oplus$. Table 2 gives the transmissivity and storage coefficient values determined and comments pertaining to the tests. In most cases, a range of values was yielded by drawdown and recovery measurements, alternate models, or alternate drawdown potential locations (as discussed above).

It is difficult to estimate the accuracy of the aquifer parameters since time limitations precluded a comprehensive error and sensitivity analysis. For the curve matching portion of the analysis the estimated accuracy of the transmissivity is a factor of 1.1 to 10 depending on the quality of the data. The estimated accuracy for the storage coefficient is a factor of 1.5 to 50. The estimated accuracy for each test analysis was taken into account when the transmissivity reference curves were prepared, as described in "The Transmissivity Iterative Calculation Routine - Theory and Numerical Implementation" (BNWL-1706).

The lack of observation wells made it difficult to obtain a meaningful value for the storage coefficient. Stallman⁴ and others confirm this observation. Unfortunately the poor accuracy of the storage coefficient values makes them practically useless for determining the Hanford Reservation storage coefficient distribution.

Results of the Boulton and Dagan model analyses seem less sensitive to slight shifts in the data matching point with the

TABLE 2. SUMMARY OF 1969 PUMP TEST RESULTS

	Aquifer Thickness (ft)	Penetration (ft)	Transmissivity (Ft ² /Day)		Effective Porosity		Permeability (Ft/Day)		Remarks
			Low	High	Low	High	Low	High	
699-2-3	60	27	2.2X10 ⁴ R	2.5X10 ⁴ D	.014	.03	3.7X10 ² R	4.2X10 ² D	Surge on recovery
699-8-32	50	27	9.0X10 ² D	1.1X10 ³ R	.002	.02	1.8X10 ¹ D	2.2X10 ¹ R	
699-17-47	75	46	1.8X10 ³ D	3.4X10 ³ R	.001	.0049	2.4X10 ¹ D	4.5X10 ¹ R	Fluctuating pump rate, may be locally confined
699-26-89			Penetrates three aquifers						
699-32-77	220	71	4.5X10 ³ D	5.7X10 ⁴ R	.0003	.026	2.1X10 ¹ D	2.6X10 ² R	
699-35-9	50	21	1.5X10 ³ D	3.7X10 ⁴ R	.0007	.054	3.0X10 ¹ D	7.4X10 ² R	May be totally penetrating
699-36-61A	67	27	9.7X10 ² D	4.0X10 ⁴ R	.0035	.19	1.4X10 ¹ D	6.0X10 ² R	Erratic data
699-36-61B	67	27	4.0X10 ² D	5.3X10 ⁴ R	.007	.10	6.0X10 ⁰ D	7.9X10 ² R	Observation well
699-40-62			No analysis, bad test data						
699-43-88	220	69	2.0X10 ³ D	1.9X10 ⁴ R	.01	.021	9.0X10 ⁰ D	8.6X10 ¹ R	Observation well
699-43-89	220	69	1.4X10 ³ D	1.8X10 ⁴ R	.00028	.12	6.4X10 ⁰ D	8.2X10 ¹ R	
699-43-104			Water level below known perforations during test						
699-47-60	40	32	1.0X10 ³ D	3.4X10 ³ R	.018	.026	2.5X10 ¹ D	2.4X10 ² R	Poor drawdown, data large drawdown, recovery by Theis analysis
699-61-66	85	44	2.7X10 ⁴ D	5.1X10 ⁴ D	.13	.65	3.2X10 ² D	6.0X10 ² D	Possible river recharge, very small drawdown, inaccurate recovery data
699-63-90	140	37	4.0X10 ⁴ D	6.3X10 ⁴ D	.021	.064	2.9X10 ² D	4.5X10 ² D	
699-71-30			Large drawdown (86%), pumping rate too high						
699-71-77	367	190	1.6X10 ⁴ D-B	4.4X10 ⁴ D-D	.0002	.006	8.4X10 ¹ D-B	1.2X10 ² D-D	Total penetration h _e = 190 (D-B) or partial penetration h _e = 367 (D-D), possible river recharge
699-77-54	74	39	5.1X10 ³ D	1.3X10 ⁴ R	.026	.039	6.9X10 ¹ D	1.8X10 ² R	Possible impermeable boundary
699-87-55			Well structure data unavailable						
199-D2-5	20	20	4.0X10 ⁴ R	6.8X10 ⁴ R	.056	.084	2.0X10 ³ R	3.4X10 ³ R	Recovery only, large drawdown, possible river recharge
199-N-14	60	30	5.5X10 ³ D	9.2X10 ³ R	.13	.27	9.2X10 ¹ D	1.5X10 ² R	Recovery only, large drawdown, possible river recharge
199-N-15	80	22	4.7X10 ⁴ D	4.2X10 ⁵ R	.15	.23	5.9X10 ² D	5.3X10 ³ R	Erratic drawdown, fast recovery
299-W21-1	200	51	5.4X10 ³ D	2.9X10 ⁴ R	.035	.096	2.7X10 ¹ D	1.5X10 ² R	May be locally confined
3099-49-E16	100	100	1.0X10 ⁵ D	1.4X10 ⁵ D	.0017	.0076	1.0X10 ³ D	1.4X10 ³ D	Recovery data inaccurate due to small values, possible river recharge
399-8-2			Penetrates two aquifers						

D - from drawdown test

R - from recovery test

D-D - drawdown test analyzed with Dagan's model

D-B - drawdown test analyzed with Bolton's model

theoretical curve than the Theis model analyses. With the Theis model a slight error in slope estimation changes the results drastically.

The overall quality of the data ranged from good to poor. Many of the wells were pumped at a high flow rate so that the drawdown quickly approached a quasi-steady state value. The flatness of the data made curve matching difficult. Three well tests could not be analyzed because of very large drawdown compared to the thickness of the aquifer (80% in one case) or excessive pump flow rate fluctuation. Erratic pump flow rates were a problem in many of the tests.

In general the recovery phases of the tests gave the most reliable aquifer parameter values because casing resistance effects were minimal and no pump flow rate variations were present.

Table 3 contains a summary of Bierschenk's well test results.¹ Most of the values were determined from recovery measurements due to the poor quality of the corresponding drawdown data.

Four wells were tested in both Bierschenk's and the 1969 group of pump tests. The data for each was analyzed using the same analytical model for both tests. Results appear in Table 4. Bierschenk's original values differ from those presented because his were based on a Theis model analysis exclusively. For three of the four there is good agreement in the transmissivity values. The storage coefficient values also agree within their accuracy estimates.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The analyzed pump tests provided the initial transmissivity values for the transmissivity distribution calculation for the Hanford Reservation VTT groundwater flow model. Unfortunately, meaningful values for storage coefficients were unobtainable by these single well tests.

The pump tests analyzed by Bierschenk should be redone on the basis of the more realistic models of Boulton or Dagan (depending on the aquifer-well relationship). Other models should be tried in conjunction with investigation of cases of possible recharge, detection of impermeable lateral boundaries, and accounting for delayed yield effects during a well test.

Care should be taken in future pump tests to initially conduct step drawdown tests for determining the effect of casing resistance and for selecting an optimum pump rate for the test. Observation wells should be installed wherever possible and the feasibility of using a neutron probe to measure storage coefficient should be investigated.

TABLE 3. SUMMARY OF PUMPING TEST RESULTS

Well No.	Transmissibility Ft ² /Day	Aquifer Thickness (feet)	Permeability Ft/Day	Remarks
699-1-18	1.0X10 ⁴	165	6.1X10	To top of clay
699-2-3	2.8X10 ²	160	1.8	Partially penetrating
699-8-17	1.0X10 ⁵	160	6.3X10 ²	Partially penetrating
699-8-32	5.6X10 ²	40	1.4X10 ²	To basalt?
699-14-27	7.1X10 ⁴	220	3.2X10 ²	Partially penetrating
699-17-5	7.5X10 ²	45	1.7X10 ²	To top of silt
699-20-20	3.0X10 ⁴	200	1.5X10 ²	Partially penetrating
699-24-33	4.5X10 ⁵	45	1.0X10 ⁴	Thickness estimated to top of Ringold
699-26-15	9.3X10 ³	45	2.1X10 ²	To top of clay
699-31-30	2.9X10 ⁵	35	7.1X10 ³	To top of Ringold
699-31-53	1.4X10 ⁴	120	1.2X10 ²	To top of clay
699-33-56	2.1X10 ⁴	90	2.3X10 ²	To top of clay
699-35-9	6.3X10 ³	130	4.8X10 ²	Partially penetrating
699-40-24	2.8X10 ⁴	150	1.9X10 ²	Partially penetrating
699-40-33	2.9X10 ²	160	1.8	To basalt
699-42-12	6.0X10 ⁴	130	4.6X10 ²	To top of clay
699-47-35	4.0X10 ⁵	20	2.0X10 ³	To basalt
699-55-50	4.0X10 ⁴	45	8.8X10 ³	To basalt
699-62-43	5.0X10 ⁴	30	1.7X10 ³	To clay
699-65-50	6.4X10 ⁴	35	1.8X10 ³	To top of Ringold
699-71-52	4.0X10 ³	50	8.0X10 ²	To top of silt
699-77-54	4.3X10 ⁴	65	6.6X10 ²	To top of clay
699-S8-19	9.1X10 ³	160	5.7X10	Partially penetrating
699-S12-3	2.8X10 ²	40	7.0X10 ²	To top of clay
199-F7-1	7.9X10 ³	15	5.3X10 ²	To top of clay
199-K-10	4.5X10 ³	85	5.3X10	To clay

TABLE 4. COMPARISON OF 1958 AND 1969 PUMP TEST DATA

Well Number	Aquifer Thickness (ft)	Penetration (ft)	Test Year	Transmissivity (Ft ² /Day)		Storage Coefficient	
				Drawdown	Recovery	Drawdown	Recovery
699-2-3	60	27	1969	7500	22,000	.11	.03
	56	27	1958	6900	35,000	.007	.35
699-8-32	50	27	1969	1000	1,100	.002	.02
	40	27	1958	(Bad data)	1,400	--	.28
699-35-9	50	50	1969	1800	11,000	.0063	.054
	40	40	1958	(Bad data)	11,000	--	.007
699-77-54	74	39	1969	5000	13,000	.026	.039
	65	30	1957	(Bad data)	50,000	--	.036

ACKNOWLEDGMENTS

This research was sponsored by the Advanced Technology Development Section, Research and Development Department, Atlantic Richfield Hanford Company. The authors are grateful for the assistance and direction provided by Dr. M. D. Veatch, Staff Hydrologist; D. J. Brown, Staff Geologist; and R. E. Isaacson, Manager of the Advanced Technology Development Section of Atlantic Richfield Hanford Company.

The efforts of Leila Counts, who provided editorial assistance, and Jan Greenwell, Loretta Howard and Velva Harris, who typed the many drafts and final reports, are also greatly appreciated.

REFERENCES

1. Bierschenk, W. H., "Aquifer Characteristics and Ground-Water Movement at Hanford." AEC R&D Report HW-60601. 1959.
2. Bierschenk, W. H., "Hydraulic Characteristics of Hanford Aquifers." AEC R&D Report HW-48916. 1957.
3. Lohman, S. W., "Ground Water Hydraulics." U.S.G.S. Prof. Paper No. 708. 1972.
4. Stallman, R. W., "Effects of Water Table Conditions on Water Level Changes Near Pumping Wells." Water Resources Res., 1, 2, 295-311. 1965.
5. Boulton, N. S., "Analysis of Data from Non-Equilibrium Pumping Tests Allowing for Delayed Yield from Storage." Proc. Inst. Civil Eng., 26, pt. 3, 469-482. 1963.
6. Dagan, G., "A Method of Determining Permeability and Effective Porosity of Unconfined, Anisotropic Aquifers." Water Resources Res., 3, 4, 1059-1071. 1967.
7. Theis, C. V., "The Relation Between the Lowering of the Piezometric Surface and the Rate and Duration of Discharge of a Well Using Groundwater Storage." Trans. Amer. Geophys. Union, 16, 519-524. 1935.
8. Hantush, M. S., "Drawdown Around a Partially-Penetrating Well." Proc. Amer. Soc. Civil Eng., 87, HY4, 83-98. 1961.
9. Hantush, M. S., "Nonsteady Flow to Flowing Wells in Leaky Aquifers." Jour. Geophys. Res., 64, 8, 1043-1052. 1959.
10. Hantush, M. S., "Drainage Wells in Leaky Water-Table Aquifers." Proc. Amer. Soc. Civil Eng., 88, HY2, 123-137. 1962.
11. Hantush, M. S., "Depletion of Storage, Leakage, and River Flow by Gravity Wells in Sloping Sands." Jour. Geophys. Res., 69, 12, 2551-2560. 1964.
12. Hantush, M. S., "Flow of Groundwater in Relatively Thick, Leaky Aquifers." Water Resources Res., 3, 2, 583-590. 1967.
13. Boulton, N. S., "The Drawdown of the Water Table Under Non-Steady Conditions Near a Pumped Well in an Unconfined Formation." Proc. Inst. Civil Eng., 3, pt. 3, 564-579. 1954.

14. Hantush, M. S., "Aquifer Tests on Partially-Penetrating Well." Proc. Amer. Soc. Civil Eng., 87, HY5, 171-195. 1961.
15. Hantush, M. S., "Hydraulics of Gravity Wells in Sloping Sands." Proc. Amer. Soc. Civil Eng., 88, HY4, 1-15. 1962.
16. Hantush, M. S., "Flow of Ground Water in Sands of Non-Uniform Thickness-3. Flow to Wells." Jour. Geophys. Res., 67, 4, 1527-1534. 1962.

APPENDIX A

TYPE CURVES AND DATA PLOTS USED TO
ANALYZE THE 1969 PUMP TESTS

APPENDIX A

The following figures contain the analytical type curves and the plotted data used to determine the transmissivity and storage coefficient values from the 1969 pump tests. The graphs for the four wells pump tested by Bierschenk¹ and reanalyzed with a model of unconfined flow are also included.

The drawdown and recovery periods for each well were graphed separately. However, all times are measured from the start of the pumping period. Match points used to link the dimensional data plots with the dimensionless analytical curves are indicated. The shifts noted on some figures represent corrections for casing head loss as discussed in the text.

FIGURE A-1. TYPE CURVES AND PUMP TEST DATA FOR WELL 199-D2-5

FIGURE A-2. TYPE CURVE AND PUMP TEST DATA FOR WELL 199-N-14

FIGURE A-3. TYPE CURVES AND PUMP TEST DATA FOR WELL 199-N-14

FIGURE A-4. TYPE CURVE AND PUMP TEST DATA FOR WELL 199-N-15

FIGURE A-5. TYPE CURVES AND PUMP TEST DATA FOR WELL 199-N-15

FIGURE A-6. TYPE CURVE AND PUMP TEST DATA FOR WELL 299-W21-1

FIGURE A-7. TYPE CURVES AND PUMP TEST DATA FOR WELL 299-W21-1

FIGURE A-8. TYPE CURVE AND PUMP TEST DATA FOR WELL 699-2-3

FIGURE A-9. TYPE CURVES AND PUMP TEST DATA FOR WELL 699-2-3

FIGURE A-10. TYPE CURVE AND PUMP TEST DATA FOR WELL 699-2-3

FIGURE A-12. TYPE CURVE AND PUMP TEST DATA FOR WELL 699-8-32

FIGURE A-13. TYPE CURVES AND PUMP TEST DATA FOR WELL 699-8-32

FIGURE A-14. TYPE CURVES AND PUMP TEST DATA FOR WELL 699-8-32

FIGURE A-15. TYPE CURVE AND PUMP TEST DATA FOR WELL 699-17-47

FIGURE A-16. TYPE CURVES AND PUMP TEST DATA FOR WELL 699-17-47

FIGURE A-17. TYPE CURVE AND PUMP TEST DATA FOR WELL 699-31-53A

FIGURE A-18. TYPE CURVES AND PUMP TEST DATA FOR WELL 699-31-53A

FIGURE A-19. TYPE CURVES AND PUMP TEST DATA FOR WELL 699-31-53B

FIGURE A-20. TYPE CURVE AND PUMP TEST DATA FOR WELL 699-32-77

FIGURE A-21. TYPE CURVES AND PUMP TEST DATA FOR WELL 699-32-77

FIGURE A-22. TYPE CURVE AND PUMP TEST DATA FOR WELL 699-35-9

FIGURE A-23. TYPE CURVES AND PUMP TEST DATA FOR WELL 699-35-9

FIGURE A-24. TYPE CURVE AND PUMP TEST DATA FOR WELL 699-36-61A

FIGURE A-25. TYPE CURVES AND PUMP TEST DATA FOR WELL 699-36-61A

FIGURE A-26. TYPE CURVE AND PUMP TEST DATA FOR WELL 36-61B

FIGURE A-27. TYPE CURVES AND PUMP TEST DATA FOR WELL 699-36-61B

FIGURE A-28. TYPE CURVE AND PUMP TEST DATA FOR WELL 699-43-88 (89A)

FIGURE A-29. TYPE CURVES AND PUMP TEST DATA FOR WELL 699-43-88 (89A)

FIGURE A-30. TYPE CURVE AND PUMP TEST DATA FOR WELL 699-43-89

FIGURE A-31. TYPE CURVES AND PUMP TEST DATA FOR WELL 699-43-89

FIGURE A-32. TYPE CURVE AND PUMP TEST DATA FOR WELL 699-47-60

FIGURE A-33. TYPE CURVE AND PUMP TEST DATA FOR WELL 699-61-66

FIGURE A-34. TYPE CURVES AND PUMP TEST DATA FOR WELL 699-61-66

FIGURE A-35. TYPE CURVE AND PUMP TEST DATA FOR WELL 699-63-90

FIGURE A-36. TYPE CURVE AND PUMP TEST DATA FOR WELL 699-71-77

FIGURE A-37. TYPE CURVE AND PUMP TEST DATA FOR WELL 699-77-54

FIGURE A-38. TYPE CURVES AND PUMP TEST DATA FOR WELL 699-77-54

FIGURE A-39. TYPE CURVES AND PUMP TEST DATA FOR WELL 699-77-54

FIGURE A-40. TYPE CURVE AND PUMP TEST DATA FOR WELL 3099-49-E16

DISTRIBUTION

<u>No. of Copies</u>	<u>Off-Site</u>
1	<u>AEC Chicago Patent Group</u> G. H. Lee
201	<u>AEC Technical Information Center</u>
2	<u>Atomic Energy Commission Headquarters</u> <u>Waste Management and Transportation</u> Germantown, Maryland 20767 Owen P. Gornley Chief, Waste Facilities Branch Robert W. Ramsey, Jr. Chief, Development Branch
2	<u>Atomic Energy Commission Site Safety</u> <u>Division</u> Directorate of Regulation 7920 Norfolk Avenue Bethesda, Maryland 20014 Ronald L. Bullard Chief, Environmental Specialist Branch W. Gamill Chief, Site Analysis Branch
2	<u>Atomic Energy Commission</u> <u>Division of Production & Material Management</u> Washington, D. C. 20545 William L. Lennemann Chief, Chemical Process James W. Pollock
2	<u>Atomic Energy Commission</u> <u>Idaho Falls, Idaho 83401</u> Dr. Adrian H. Dahl Chief, Environmental Science Branch B. L. Schmalz

<u>No. of Copies</u>	<u>Off-Site</u>
3	<u>U. S. Geological Survey</u> 2100 M. Street Washington, D. C. 20037 George Debuchananne, Director M. K. Hubbert Research Geophysicist Dallas Peck
1	<u>U. S. Geological Survey</u> Menlo Park, California 94025 Jacob Rubin
1	<u>U. S. Geological Survey</u> Groundwater Branch Denver, Colorado R. W. Stallman
1	<u>U. S. Geological Survey</u> Water Resources Division Bldg. 53, Room H-2910 Lakewood, Colorado 80225 J. D. Bredehoeft
1	<u>U. S. Geological Survey</u> Water Resources Division P.O. Box 917 Council Bluffs, Iowa 51501 O. J. Ramsvick Supervisory Hydrologist
1	<u>U. S. Geological Survey</u> Albuquerque, New Mexico Dr. C. V. Theis
1	<u>U. S. Geological Survey</u> Water Resources Division P.O. Box 2857 Raleigh, North Carolina Ralph C. Heath District Chief

<u>No. of Copies</u>	<u>Off-Site</u>
2	<u>U. S. Bureau of Mines</u> 4800 Forbes Avenue Pittsburgh, Pennsylvania 15213 George Evans Robert W. Van Dolah
3	<u>U. S. Bureau of Mines</u> Spokane Mining Research Laboratory N. 1430 Washington St. Spokane, Washington 99201 Robert C. Bates Dan Keeley Michael M. McDonald
1	<u>U. S. Forestry Service</u> Intermountain Forest and Range Experiment Station Boise, Idaho 83702 Dr. Walter F. Meghan Research Hydrologist
1	<u>Environmental Protection Agency</u> Crystal Mall Washington, D. C. 20460 Arnold Joseph
1	<u>Environmental Protection Agency</u> Office of Research & Monitoring Edison Water Quality Office Edison, New Jersey 08817 Richard Field
1	<u>National Water Commission</u> 800 N. Quincy Arlington, Virginia 22209 Dr. John S. Gladwell
1	<u>USDA-ARS</u> <u>U. S. Water Conservation Laboratory</u> 4331 East Broadway Phoenix, Arizona 85040 Dr. Herman Bouwer Hydraulic Engineer

No. of
Copies

Off-Site

1	<u>USDA-ARS</u> U. S. Salinity Laboratory P.O. Box 672 Riverside, California 92502 Dr. Jan Van Schilfgaarde, Director
1	<u>USDA-ARS</u> Engineering Research Center CSU Foothills Campus Fort Collis, Colorado 80521 Dr. David A. Woolhiser Hydraulic Engineer
1	<u>USDA-ARS</u> Northwest Watershed Research Center P.O. Box 2700 Boise, Idaho 83701 Walter J. Rawls, Hydrologist
1	<u>USDA-ARS</u> P.O. Box 1096 Boise, Idaho 83701 J. L. Robins
1	<u>USDA-ARS</u> Twin Falls, Idaho M. E. Jensen
1	<u>USDA-ARS</u> Snake River Conservation Research Center Route 1, Box 186 Kimberly, Idaho 83341 Dr. Marvin E. Jensen, Director
1	<u>USDA Hydrograph Laboratory</u> Plant Industry Station Soils Building Beltsville, Maryland 20705 H. N. Holton, Director
1	<u>USDA-ARS</u> Plant Industry Station Beltsville, Maryland 20705

No. of
Copies

Off-Site

Dr. Donald L. Brakensick
Chief Engineer

1 USDA Sedimentation Laboratory
P.O. Box 30
Oxford, Mississippi 38655

A. R. Robinson, Director

1 USDA-ARS
Southern Region
Stoneville, Mississippi 38776

John C. Stephens, Director

1 USDA-ARS
North Central Watershed Research Center
P.O. Box 916
Columbia, Missouri 65201

Dr. C. R. Amerman
Hydraulic Engineer

1 USDA-ARS
North Appalachian Experimental Watershed
Coshocton, Ohio 43812

Dr. W. M. Edwards
Soil Scientist

1 USDA
P.O. Box 400
Chickasha, Oklahoma 73018

Harry B. Pionke

1 USDA-ARS
Northeast Watershed Research Center
Pennsylvania State University
111 Research Building 3
University Park, Pennsylvania 16802

Dr. A. S. Rogowski
Soil Scientist

1 National Academy of Science
U. S. National Committee for the IHD
2101 Constitution Avenue
Washington, D. C. 20418

Dr. Leo Heindl
Executive Secretary

No. of
Copies

Off-Site

1	<u>National Academy of Science</u> Committee on Radioactive Waste Management National Research Council 2101 Constitution Avenue Washington, D. C. 20418 Dr. Cyrus Klingsberg Technical Secretary
1	<u>National Science Foundation</u> Division of Advanced Technology Application 1800 6th Street N.W. Washington, D. C. 20530 Ray Zahradnik
1	<u>U. S. Naval Civil Engineering Laboratory</u> Port Hueneme, California 93043 Dr. James J. Der
2	<u>Robert S. Kerr Water Research Center</u> P.O. Box 1198 Ada, Oklahoma 74820 Dr. J. W. Keeley Marion R. Scalf
1	<u>Alabama Geologic Survey</u> P.O. Drawer 0 University, Alabama 35486 Phil Lammereaux State Geologist
1	<u>Southwest Rangeland Watershed Research Center</u> 442 E. Seventh Street Tucson, Arizona 85705 Dr. R. Smith
1	<u>California Dept. of Water Resources</u> Sacramento, California Helen J. Peters

No. of
Copies

Off-Site

1	<u>Idaho Bureau of Mines & Geology</u> <u>University of Idaho</u> Moscow, Idaho 83843 Dr. Roy E. Williams
1	<u>Idaho Dept. of Water Administration</u> <u>State House, Annex 2</u> Boise, Idaho 83707 Keith R. Higginson, Director
1	<u>Idaho Water Resources Board</u> <u>Boise, Idaho</u> R. R. Lee
1	<u>Illinois State Water Survey</u> <u>P.O. Box 232</u> Urbana, Illinois 61801 Keros Cartwright
1	<u>State Geological Survey of Kansas</u> <u>University of Kansas</u> Lawrence, Kansas 66044 Dr. John C. Halepaska Chief, Water Resources Section
1	<u>State of Maine</u> <u>Environmental Improvement Commission</u> Augusta, Maine 04330 Steven D. Freedman
1	<u>St. Anthony Falls Hydraulic Laboratory</u> <u>Mississippi River at 3rd Avenue East</u> Minneapolis, Minnesota 55414 Professor C. Edward Bowers
2	<u>Desert Research Institute</u> <u>Center for Water Resources Research</u> Reno, Nevada Dr. Clinton Case G. B. Maxey

<u>No. of Copies</u>	<u>Off-Site</u>
1	<u>State of North Carolina</u> <u>Groundwater Division</u> Water and Air Resources Raleigh, North Carolina 27611 Harry M. Peek, Chief
1	<u>Water Quality Management Laboratory</u> <u>Rt. 2, Box 322A</u> Durant, Oklahoma 74701 V. L. Hauser
1	<u>State of Oregon</u> <u>516 Public Service Bldg.</u> Salem, Oregon 97310 Chris Wheeler State Engineer
1	<u>Texas Water Development Board</u> <u>Systems Engineering Division</u> P.O. Box 13087 Austin, Texas 78711 Lial F. Tischler
1	<u>Agencies for Environmental Conservation</u> <u>Montpelier, Vermont 05602</u> Dr. Martin L. Johnson Secretary
1	<u>State of Washington</u> <u>Department of Ecology</u> P.O. Box 829 Olympia, Washington 98504 John R. Raymond
1	<u>Washington State Water Research Center</u> <u>Pullman, Washington 99163</u> James Crosby, III Geologist
1	<u>Atomic Industrial Forum, Inc.</u> <u>475 Park Avenue South</u> New York, New York 10016 Gerald V. Halvorsen Environmental Projects Manager

<u>No. of Copies</u>	<u>Off-Site</u>
1	<u>Computer Sciences Corp.</u> <u>Federal Building</u> Richland, Washington 99352 R. W. Nelson
1	<u>Sandia Laboratories</u> <u>Division 5166</u> Albuquerque, New Mexico 87115 Fred Norwood
1	Arthur M. Piper #3 Sonoma Lane Carmel, California 93921
1	<u>Alyeska Pipeline Service Co.</u> <u>2100 Travis Street</u> Houston, Texas 77002 Dr. Maurice D. Veatch
1	<u>E. I. duPont deNemours & Co., Inc.</u> <u>Savannah River, South Carolina</u> J. C. Corey
1	<u>University of Arizona</u> <u>Office of Arid Lands Studies</u> 1201 East Speedway Blvd. Tucson, Arizona 95719 Dr. Ken Faster
1	<u>University of Arizona</u> <u>Dept. of Agriculture Chemistry and Soils</u> Tucson, Arizona 85721 Dr. Gordon Dutt
2	<u>University of Arizona</u> <u>Dept. of Hydrology and Water Resources</u> 200-E Old Psychology Tucson, Arizona 95721 Dr. A. K. Tyagi Dr. Chester C. Kisiel

No. of
Copies

Off-Site

2	<u>University of Arizona</u> <u>Tucson, Arizona 95721</u> E. S. Simpson A. W. Warrick
2	<u>University of California</u> <u>Berkeley, California 94720</u> Dr. Warren Kauffman P. A. Witherspoon Dept. of Civil Engineering
3	<u>University of California at Davis</u> <u>Dept. of Water Sciences and Engineering</u> <u>Davis, California 95616</u> J. N. Luthin Don Nielson Dr. Verne H. Scott
1	<u>University of California at Riverside</u> <u>College of Biological & Agricultural</u> <u>Sciences</u> <u>Riverside, California 92507</u> Dr. N. T. Coleman
3	<u>Stanford University</u> <u>Department of Civil Engineering</u> <u>Stanford, California 94305</u> Paul Kruger Henry J. Ramey J. B. Franzini
1	<u>Stanford University</u> <u>School of Earth Sciences</u> <u>Dept. of Geology</u> <u>Stanford, California 94305</u> E. Aguado

<u>No. of Copies</u>	<u>Off-Site</u>
1	<u>Georgia Institute of Technology</u> <u>School of Civil Engineering</u> Atlanta, Georgia 30332 Dr. J. R. Wallace
1	<u>University of Idaho</u> <u>Moscow, Idaho 83843</u> Dr. Delbert Fitzsimmons Head, Agricultural Engineering
2	<u>University of Illinois</u> <u>Urbana, Illinois 61801</u> A. Klute Professor Ven Te Chow Hydrosystems Laboratories
1	<u>Purdue University</u> <u>Dept. of Agricultural Engineering</u> <u>West LaFayette, Indiana 47907</u> Emru D. Millette
1	<u>Iowa State University</u> <u>Ames, Iowa</u> D. Kirkham
1	<u>University of Kansas</u> <u>Water Resources Institute</u> <u>Lawrence, Kansas 66044</u> Don W. Green
1	<u>University of Kentucky</u> <u>Department of Mechanical Engineering</u> <u>Lexington, Kentucky 40506</u> C. T. Hahn
1	<u>Harvard University</u> <u>School of Public Health</u> <u>Boston, Massachusetts 02138</u> Dr. D. W. Moeller

<u>No. of Copies</u>	<u>Off-Site</u>
1	<u>Massachusetts Institute of Technology</u> 77 Massachusetts Avenue Room 48-263 Cambridge, Massachusetts 02139 Dr. Donald Harleman
1	<u>University of Minnesota</u> Department of Geology and Geophysics 2D Pillsbury Hall Minneapolis, Minnesota 55455 Hans Olaf Pfannkuch
1	<u>University of Minnesota</u> Department of Civil Engineering Minneapolis, Minnesota 55418 H. Steform
2	<u>University of Nebraska</u> School of Civil Engineering Lincoln, Nebraska 68503 Mark J. Hammer Warren Viessman, Jr.
1	<u>Princeton University</u> School of Engineering/Applied Science Department of Civil and Geological Engineering Princeton, New Jersey 08540 Dr. Robert W. Cleary
2	<u>Princeton University</u> Department of Civil & Geological Engineering Princeton, New Jersey 08540 R. J. M. DeWiest G. F. Pinder
1	<u>New Mexico State University</u> Department of Agronomy P.O. Box 3Q Las Cruces, New Mexico 88001 P. J. Wierenga

No. of
Copies

Off-Site

1	<u>State University of New York at Buffalo</u> <u>Dept. of Mechanical Engineering</u> Buffalo, New York 14214
	Ralph T. Cheng
1	<u>State University of New York</u> <u>Dept. of Civil Engineering</u> Buffalo, New York 14214
	Dr. Ralph Rumer
2	<u>Cornell University</u> <u>School of Civil Engineering</u> B22 Bailey Hall Ithaca, New York 14850
	W. H. Brutsaert
	Winton Covey
2	<u>Oregon State University</u> <u>Corvallis, Oregon 97331</u>
	Dr. Larry Boersma Professor of Soils
	Dr. Royal H. Brooks Professor of Agricultural Engineering
1	<u>Drexel Institute of Technology</u> <u>Philadelphia, Pennsylvania 19104</u>
	Irwin Remson
1	<u>Vanderbilt University</u> <u>Nashville, Tennessee 37203</u>
	Dr. Frank L. Parker
1	<u>Utah State University</u> <u>College of Engineering</u> <u>Dept. of Agriculture and Irrigation</u> <u>Engineering</u> Logan, Utah 84321
	Dr. L. G. King

<u>No. of Copies</u>	<u>Off-Site</u>
1	<u>Utah State University</u> Utah Water Research Laboratory College of Engineering Logan, Utah 84321 J. Paul Riley
1	<u>Utah State University</u> Logan, Utah 84321 Dr. Roland W. Jeppson Associate Prof. of Civil Engineering
1	<u>Utah State University</u> Logan, Utah 84321 C. G. Clyde
1	<u>University of Wyoming</u> Laramie, Wyoming 82070 Dr. Paul A. Rechard Director, Water Resources Research Institute
2	<u>Washington State University</u> Dept. of Civil Engineering 148 Sloan Hall Pullman, Washington 99163 Dr. Donald L. Bender Dr. David Higgins
2	<u>Washington State University</u> Dept. of Agronomy & Soils Pullman, Washington 99163 Dr. Walter H. Gardner Dr. Eugene Thompson
1	<u>Washington State University</u> Albroom Hydraulic Laboratory Pullman, Washington 99163 Dr. John F. Orsborn, Head

<u>No. of Copies</u>	<u>Off-Site</u>
1	<u>University of Washington</u> <u>Department of Geology</u> Seattle, Washington 98105 Dr. Howard Coombs
2	<u>University of Wisconsin</u> <u>Department of Soil Science</u> Madison, Wisconsin 53706 W. R. Gardner P. Saffigna
1	<u>Water Conservation and Irrigation</u> <u>Commission</u> P.O. Box 220R Royal Exchange Sydney, 2000, Australia Frans R. Kalf
1	<u>University of New South Wales</u> <u>School of Civil Engineering</u> Sydney, Australia Dr. K. K. Watson
1	<u>Institut für Geophysik</u> <u>Technische Hochschule</u> Karlsplatz 13 A-1040 WIEN Österreich Austria A. E. Scheidegger
1	<u>University of British Columbia</u> <u>Vancouver, B. C., Canada</u> Dr. Allen Freeze
1	<u>Dept. of Mines and Natural Resources</u> <u>Water Resources Branch</u> 693 Taylor Avenue Winnipeg 9, Manitoba, Canada Frank W. Render

No. of
Copies

Off-Site

1	<u>University of Waterloo</u> Department of Earth Science Waterloo, Ontario, Canada Richard G. Jackson
1	<u>University of Waterloo</u> Department of Civil Engineering Faculty of Engineering Waterloo, Ontario, Canada John F. Pickens
1	<u>McMaster University</u> Department of Civil Engineering Hamilton, Ontario, Canada Dr. William James
2	<u>Ontario Water Resources Commission</u> 135 St. Clair Avenue West Toronto 7, Ontario, Canada Donald N. Jeffs Bob Ostry
1	<u>Department of the Environment</u> 4905 Dufferin Street Downsview, Ontario, Canada Dr. Aloysius K. Lo
2	<u>Department of the Environment</u> C-244, No. 8 Temporary Bldg. Inland Waters Branch Ottawa, Canada R. E. Jackson Dennis Lawson
1	<u>Institut de Mecanique (I.M.G.)</u> Domaine Universitaire B. P. 53 Centre de Tri 38041 Grenoble-Cedex, France Georges Vachaud

<u>No. of Copies</u>	<u>Off-Site</u>
1	<u>M. R. Engineering College</u> <u>Jaipur-302004, India</u> Dr. R. D. Verma Prof. of Civil Engineering
1	<u>University College</u> <u>Upper Merrion Street</u> <u>Dublin, 2 Ireland</u> Dr. James C. I. Dooge Professor of Civil Engineering
1	<u>Department of Mechanical Engineers,</u> <u>I.I.T. Kharagkur,</u> <u>S.E. Ry, India</u> R. G. Mokadom
3	<u>Technion-Israel Institute of Technology</u> <u>Haifa, Israel</u> J. Bear Shragga Irmay Dan Zaslavsky
1	<u>Agricultural Research Organization</u> <u>The Volcani Center</u> <u>The Institute of Soils and Water</u> <u>P.O.B. 6</u> <u>Bet Dagan, Israel</u> Shlomo P. Neuman
1	<u>Food & Agriculture Organization of the UN</u> <u>Land and Water Development Division</u> <u>Water Resources & Development Service</u> <u>Via Delle Terme Dl Caracalla</u> <u>00100-Rome, Italy</u> R. G. Thomas
1	<u>Kyoto University</u> <u>Kyoto, Japan</u> Yoriteru Inoue

No. of
Copies

Off-Site

1 Explorade En Produktie Laboratorium
 c/o Koninklijke/Shell
 Volmerlaan 6
 Ritswijk (Z.H.), The Netherlands

A. M. Schaaps

1 University of Canterbury, N.Z.
 Dept. of Civil Engineering
 Christ Church 1, New Zealand

Bruce W. Hunt

On-Site Hanford

1 AEC/R1 Patent Attorney

R. M. Poteat

7 AEC Richland Operations Office

O. J. Elgert
J. L. Rhoades
P. J. Holsted (2)
E. B. Jackson
P. G. Rhoades
R. B. Goranson
B. J. Melton

69 Atlantic Richfield Hanford Co.

G. E. Backman
G. L. Borsheim
D. J. Brown
L. E. Bruns
M. H. Campbell
W. M. Harty
R. E. Isaacson (2)
L. M. Knights
C. W. Malody
B. J. McMurray
M. C. Metz
H. P. Shaw
A. E. Smith
P. W. Smith
W. J. Van Slyke
ARHCO File
G. A. Nicholson

No. of
Copies

On-Site Hanford

3

Westinghouse Hanford Co. HEDL

R. B. Hall

29

Battelle-Northwest

D. B. Cearlock
J. P. Corley
J. R. Eliason
K. L. Kipp
D. E. Olesen
A. E. Reisenauer
D. D. Tillson
R. C. Routson
R. J. Serne
D. R. Friedrichs
S. W. Ahlstrom
R. G. Baca
A. Brandstetter
R. D. Mudd
R. W. Wallace
J. J. Fuquay
A. J. Shuckrow
L. E. Addison
Tech. Information
Tech. Pubs.

8

United Nuclear, Inc.

C. D. Corbit
F. E. Owen