see pocket 3 for attachment

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NOV 4 1983

Mr. O. L. Olson, Project Manager
Basalt Waste Isolation Project Office
U. S. Department of Energy
Richland Operations Office
P. O. Box 550
Richland, WA 99352

Dear Mr. Olson:

We appreciate the opportunity of reviewing a draft copy of document SD-BWI-TS-007, "Applicability of the Van der Kamp Method in Slug Test Analysis." The report has been examined by the hydrogeology staff of the Division of Waste Management; by Golder Associates, Inc.; and by Roy Williams and Associates, Inc.. This letter transmits to you the comments of the NRC staff. Also, attached for your information are copies of the comments from Golder Associates and Roy Williams and Associates.

Principal Comments

1. The summary of the theoretical basis for the development of the Van der Kamp method of slug test analysis in shallow systems, for which it was originally designed, is brief but adequate for a document of this nature. However, we are concerned that the theoretical development does not adequately highlight certain critical simplifying assumptions that are important in considering the application of the method in the deep basalts of the Hanford Reservation. In particular, the effects of well (tubing) friction cannot be neglected (see Attachment 2, pages 6-10), and a more detailed analysis of wellbore compressibility is needed (Attachment 2, pages 10-11).

2. The section on test procedures is not sufficiently comprehensive to answer some fundamental questions concerning the apparatus installed in the borehole and the methods used to produce the pulse. For example,

   o Is the borehole packed off at the top of the column or left open to the atmosphere with a pressure transducer located below the water surface?

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- o Are the transducers located near the bottom of the hole near the test interval or near the surface of the water column in the borehole?

- o What is the time interval involved in creating the pulse?

Answers to these particular questions and a more thorough discussion of test procedures generally are important to the general question of the applicability of the Van der Kamp method.

3. A reasonable correlation appears to exist between results obtained by the Van der Kamp method and other analysis methods for the selected test cases cited in the document. However, the correlation is less apparent upon examination of a larger selection of test data (Attachment 2, Figure 2 and Table 3). Using Figure 8 of the subject document and the test data obtained by the NRC staff at the July, 1982 hydrogeology workshop held in Richland, Washington, approximate transmissivities determined from the Van der Kamp method were plotted against effective length of the water-filled tubing (Attachment 3, Figures 1 and 2). Based on under-damped (Van der Kamp) water-level response, seven transmissivity values plot in the over-damped (wrong) region (Figure 1); based on over-damped response, seven values plot in the under-damped (wrong) region (Figure 2). In the case considered in Figure 2, 28 of 45 data points cannot be plotted on the figure becuase the transmissivity values are less than 10'ft /day. The uncertainty associated with transmissivity values calculated using the Van der Kamp method appears to be substantially greater than that indicated by the four selected test cases presented in the draft document.

4. The document has not adequately assessed the validity of past tests or developed clear acceptability criteria for future applications of the method. For example, Van der Kamp (Water Resources Research, V. 12, no. 1, 1976) developed criteria to evaluate conditions under which frictional losses may be neglected for both laminar and turbulent flow. Application of the appropriate criterion to test data for DC-14 and RRL-2 indicates that the criterion is not met (Attachment 2, pages 9-10). Preliminary analysis of the data for the Ford well also suggests that the criterion is not met for the test case cited in the subject document.

While potential problems with the DC-14 tests are noted in the document, the potential for error in the other test results is not

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DATE	11/ /83	11/ /83	11/ /83	11/ /83	11/ /83		

evaluated. As a necessary step in demonstrating the applicability of the method in specific cases, BWIP should establish values for the criteria which are judged to be acceptable, and then apply that (and other relevant acceptance criteria) to each test.

Conclusion

BWIP document SD-BWI-TS-007 has responded to some points raised by the NRC staff and its contractors with respect to the Van der Kamp method of analysis for slug tests. However, significant uncertainty still remains about the general applicability of the method for conditions typical of the deep basalts at BWIP. Furthermore, the subject document does not provide an adequate procedure or present all of the information needed by the NRC to perform an independent assessment of the data already developed using the Van der Kamp method.

If you have any questions about this review, please contact me, or have Dr. Spane contact Dr. Tilak Verma or Mr. Mark Logsdon of the Division of Waste Management

Sincerely,

"ORIGINAL SIGNED BY"

Robert J. Wright,
Senior Technical Advisor
Repository Projects Branch
Division of Waste Management

Attachments:
As stated

*See previous concurrence.

OFC	WMRP	WMGT	WMGT	WMRP	WMRP		
NAME	MLogsdon:dm*	TVerma *	MKnapp *	RJWright *	HJMiller		
DATE	11/ /83	11/ /83	11/ /83	11/ /83	11/ /83		

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Sincerely,

Robert J. Wright,
Senior Technical Advisor
Repository Projects Branch
Division of Waste Management

Attachments:
As stated

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see 101.2
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11/4/83

Attachment 1

SPECIFIC COMMENTS

Comment	Pages	
1	2-3	The staff considers that 4 test examples are not enough to come to the conclusion that "the approximate solution presented by Van der Kamp (1976) for analysis of the under-damped, slug test response appears to be valid for well-test system characteristics commonly encountered on the Hanford site" (Finding 1, page 3).
2	3	"Finding 2" - This is questionable based on following comments. Also, trend is different. Krauss and Van der Kamp's data indicated that slug tests generally gave higher values than pumping test analyses. This report shows the opposite.
3	19	Paragraph 2 - A simple statistical analysis may be helpful here. Regress a straight line through data and test if slope is significantly different from 1 and intercept significantly different from zero.
4	19	Paragraph 4 - What percentage in Wanapum Basalt exhibit under-damped responses?
5	22	Paragraph 3 - It may be helpful in arriving at a conclusion if one included the data developed from the Hanford cases with those reported by Krauss and Van der Kamp and repeated statistical test mentioned in Comment 3.
6	25	First four transmissivity values appear to be incorrect based on the a and b values given in the table and equation 25. The correct values appear in the appendix and are 10 x greater than those reported in the table.
7	25	First two "d" values appear to be incorrect based on values given for γ and ω, and equation 19 and 20. The correct values appear in the appendix and are 10x greater than those reported in table.

8	25	Why is there such a large discrepancy between injection - and withdrawal -determined transmissivities in RRL-2 Composite Umtanum Flow? This deserves further comment in text.
9	27-29	The staff cannot account for γ values reported in Table 3. Using methodology given in report, reported γ's are consistently off by a factor of two for last three tests. Is there an error in Equation 33?
10	27	Paragraph 1 - If comment 6 is correct and there are no errors in Table 3, there is a significant difference in T's between Grande Ronde slug test and pumping test.
11	27	Paragraph 4 - If comment 9 is correct and there are not errors in Equation 33, this is no longer true.
12	30	Paragraph 2 - If comment 6 is true, this statement is incorrect.

ATTACHMENT 2

MEMORANDUM

TO: Mark Logsdon
FROM: Jerry Rowe
SUBJECT: Contract No. NRC-02-82-045
BWIP Hydrogeology
Review of Van der Kamp Method
Letter No. 57

DATE: October 19, 1983
JOB No.: 823-1033

(B7373)

1.0 INTRODUCTION

This memorandum follows a request by the NRC that Golder Associates, Inc., review and comment on the document entitled "Applicability of the Van der Kamp Method in Slug Test Analysis" (by F.A. Spane, Rockwell Hanford Operations, SD-BWI-TS-007, 1983) and, more generally, upon the applicability of the Van der Kamp method for slug test analysis at the BWIP site.

Slug tests have been utilized by Rockwell Hanford Operations (RHO) to measure in situ transmissivities of basalt formations. Slug tests are relatively simple and inexpensive to perform and are commonly used in single boreholes. In performing a slug test, water is instantaneously added to or withdrawn from the hole and the resulting water level changes are monitored. The water level typically returns to the equilibrium level in an approximately exponential manner. For tests performed in highly transmissive formations, it is sometimes observed that the water level oscillates about the equilibrium level with amplitudes that decrease exponentially. This so-called "underdamped" response was first investigated by Bredehoeft et al (1966) using an electric analog. They concluded that oscillations result from inertial effects of the mass of water in the riser pipe. Van der Kamp (1976) derived an approximate analytical solution for the underdamped case and proposed a method for calculating transmissivity based on characteristics of the measured response.

According to the document being reviewed herein, approximately thirty percent of basalt interflows in which slug tests have been performed exhibit an

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underdamped response. For many intervals alternative tests were conducted (e.g., single-hole pump tests) and results were analyzed to calculate tranmissivity. However, there are a significant number of intervals in which pump tests are not available and the Van der Kamp method provides the only means of calculating transmissivity. Obviously, it would be of benefit to RHO if it can be demonstrated that the Van der Kamp method yields acceptable estimates of transmissivity in the absence of other tests methods.

The NRC staff has expressed concern as to the applicability of the Van der Kamp method at the BWIP site. This concern arises because of the approximations used in developing the Van der Kamp method and because of the apparent lack of consistency between transmissivities calculated from slug tests in given intervals using the Van der Kamp method and those calculated for the same intervals using other testing and analytical methods. These concerns were originally expressed by the NRC staff at a hydrogeology workshop in July, 1982.

In this memorandum a brief description of the Van der Kamp method is given, conclusions given by RHO regarding the applicability of the method are summarized, and the results of Golder Associates review of the subject document are presented.

2.0 Description of the Van der Kamp Method

The Van der Kamp (1976) solution treats the wellbore and aquifer system as a damped harmonic oscillator. A simple analogy for this system consists of a weight suspended from a spring and emersed in a viscous fluid. Under appropriate conditions, if the weight is displaced and then released, it will oscillate about its equilibrium position with an angular velocity of w radians per second (or a time period of $P = 2\Pi/w$ seconds per cycle). Frictional forces exerted by the viscous fluid will result in amplitudes of oscillation that decrease exponentially with time in relation to a damping factor (γ). For the wellbore-aquifer system of interest, the mass of fluid in the wellbore is analogous to the suspended weight, hydraulic head changes in the aquifer represent the spring, and frictional forces are exerted by fluid moving in the aquifer. Electric analogue studies by Bredehoeft et al (1966) for such a system predict an underdamped harmonic response for slug tests performed in highly transmissive aquifers.

A complete analytical solution for the wellbore-aquifer system would be exceedingly complex and therefore Van der Kamp introduced the following simplifying assumptions:

- o hydraulic frictional forces in the wellbore are negligible
- o water level displacements are very small compared to the effective length of the water column
- o hydraulic head is constant along the well filter
- o the length of the well filter is not large compared to the length of the water column in the riser pipe
- o fluid in the wellbore is incompressible and confined wellbore storage at the filter is negligible
- o linear flow conditions exist in the aquifer (i.e., flow conditions for which Darcy's law is valid)
- o no borehole skin effect or extensive zone of invasion exists in the aquifer
- o the aquifer is homogeneous, isotropic, confined, and of infinite radial extent.

Van der Kamp further assumed that the solution was given by the classic equation for an underdamped harmonic oscillator. This assumption seems reasonable based on the electric analogue results of Bredehoeft et al (1966) and observed field responses for the underdamped case. Van der Kamp cautioned that the assumed solution may not apply to situations where oscillations are damped very rapidly.

Using further simplifying assumptions, Van der Kamp derived approximate equations which relate wellbore-aquifer parameters (in particular transmissivity) to measured values of angular velocity (w) and the damping constant (γ). He gave criteria for evaluating the conditions under which the approximate equations are valid. As a corroborative check, Van der Kamp gave two equations for calculating the effective length of the water column; one related to measured response parameters and one based on a priori information on the wellbore geometry. If the assumed wellbore-aquifer model is truly representative of the real system, the two equations should give comparable values. For the cases considered in Van der Kamp (1976) the agreement was relatively good.

Van der Kamp provided additional criteria for evaluating when frictional losses in the wellbore can be safely neglected. His criteria are somewhat nonconservative in that frictional losses are assumed to occur only in the riser pipe. His criteria do not account for frictional losses at the well filter (i.e., skin effect) or flow constrictions in the test tool (e.g., shut-in valve).

Van der Kamp concludes that estimates of transmissivity from an underdamped well response obtained by his method are probably accurate to within a factor of two.

3.0 Summary of RHO Findings

The approach taken by RHO to evaluate the Van der Kamp method primarily depends upon developing a comparison between values of transmissivity determined by the Van der Kamp analysis and values determined for the same test intervals by other methods. Four test examples were chosen by RHO based upon the following stated criteria:

- the availability of transmissivity values obtained from independent pumping test analysis
- the absence of complicating features (e.g., boundary effects, multiple aquifer response, multiphase conditions, etc.) as indicated from pumping test analysis
- the representation of a wide range of transmissivities
- the representation of test examples exhibiting a variety of depths and well-test system characteristics commonly encountered at Hanford.

In the four cases considered, transmissivities determined by the Van der Kamp method differed from those determined from single-hole pumping test data by a factor of three or less. This level of variability is consistent with similar comparisons reported in Van der Kamp (1976) and Krauss (1977).

The document also discusses the mechanics and governing equations for the underdamped response, the approximate solution described by Van der Kamp, and relevant assumptions and limitations of the method. However, it does not provide any significant extension of these topics beyond the discussion provided by Van der Kamp (1976).

The major conclusions reached by RHO include:

1. "Based on the test examples considered in this study, the approximate solution presented by Van der Kamp (1976) for analysis of the underdamped, slug test response appears to be valid for well-test system characteristics commonly encountered on the Hanford Site.

2. Comparison of transmissivity values obtained from pumping test and underdamped, slug test analysis generally are in good agreement and differ by a factor of three or less for the Hanford test examples examined. This level of variability is consistent with similar comparisons reported in Van der Kamp (1976) and Krauss (1977).

3. Due to uncertainties of analysis input parameters, hydraulic properties determined from underdamped, slug test analyses should continue to be used by BWIP as a corroborative check for estimates obtained from longer duration, constant discharge and/or constant drawdown tests."

RHO also recommends that "for cases where hydraulic properties are unavailable from long duration tests, transmissivities reported for underdamped, slug tests should be accompanied with adequate discussions of test limitations and results from previous comparative test studies."

4.0 DISCUSSION

Golder Associates review of the subject document and the general applicability of the Van der Kamp method is discussed below. Several of the basic assumptions made by Van der Kamp are examined to determine if they could affect the response measured in underdamped slug tests at the BWIP site. Those include the assumptions of negligible frictional force in the riser pipe and incompressible wellbore storage. In addition, data obtained during the BWIP/NRC workshop at Richland in July, 1982 are examined to compare transmissivities determined by Van der Kamp analysis with those determined by other methods.

4.1 Frictional Forces in the Wellbore

Van der Kamp's solution requires that laminar and turbulent head losses inside the riser pipe are negligible, and in his paper he provides criteria for evaluating when wellbore friction can be safely neglected. In assessing the four test examples, RHO concluded that "in most cases, turbulent and/or significant frictional [i.e., laminar] head loss effects were dissipated within the initial oscillitory period, which allowed late-time analysis of the slug test data." This conclusion was evidently based on the fact that later time data generally conformed to an ideal curve for an underdamped harmonic oscillator, while early time data were somewhat scattered. RHO did not evaluate the effects of well friction based on Van der Kamp's criteria.

The theoretical development presented in the document section entitled "Harmonic Motion Analysis" indicates that frictional force must be a linear function of velocity in order to obtain the classic underdamped response. For turbulent flow conditions, head loss in the riser pipe is proportional to the square of velocity, and thus a departure from the ideal curve is expected. However, when the flow regime is laminar, frictional head loss is directly proportional to velocity (a linear function) and the harmonic response should therefore follow the ideal curve. In the BWIP tests, early time data not corresponding to the ideal response may reflect turbulent flow conditions in the riser pipe. Later time data, falling on the underdamped response curve, probably represent laminar flow conditions, but this does not imply that frictional head losses have dissipated. Thus, the RHO criteria for frictional effects are probably not valid for evaluating laminar flow head losses in the riser pipe.

If laminar flow well losses are significant during an underdamped slug test, the data should still follow an ideal curve, but parameters defining that curve are then related to frictional properties of both the aquifer and the wellbore. In this case, the Van der Kamp method should tend to underestimate aquifer transmissivity.

Analyses were conducted to estimate the effect of frictional losses in the wellbore. The typical underdamped response shown in Figure 1 is described by the equation

$$X = X_0 \, exp(-\gamma t) \, cos(wt) \tag{1}$$

where X is the water level variation from static level, X_0 is the initial water level displacement, γ is the damping constant defined by Van der Kamp, w is the angular frequency of water level oscillation, and t is time.

Differentiating (1) with respect to time and noting that the maximum slope of the oscillating response in Figure 1 occurs at $wt = (2n-1)\Pi/2$, where n = 1, 2, 3, ..., an expression for maximum velocity is obtained,

$$V_{max} = X_0 \, w \, exp(-\gamma t) \tag{2}$$

The Reynolds number for a smooth pipe (e.g., riser pipe) is expressed as

$$R = \frac{2 \rho V r_c}{\mu} \tag{3}$$

where ρ is fluid density, V is velocity, r_c is the pipe radius, and μ is the dynamic viscosity. Substituting the expression for V_{max} into (3) yields

$$R = \frac{2 \rho r_c}{\mu} X_0 \, exp(-\gamma t) \tag{4}$$

Head loss in the wellbore is expressed by the Darcy-Weisbach equation as

$$h_w = \frac{f\ L\ V^2}{4\ g\ r_c} \tag{5}$$

where f is the friction factor, L is the riser pipe length, and g is gravitational acceleration. Substituting the expression for V_{max} in equation (2) yields

$$h_w = \frac{f\ L}{4\ g\ r_c} [X_0\ w\ exp(-\gamma t)]^2 \tag{6}$$

For laminar flow (R<2100) the friction factor is expressed by

$$f = \frac{64}{R} \tag{7}$$

For turbulent flow (R>4000) the friction factor is expressed approximately by

$$f = \frac{0.316}{R^{1/4}} \tag{8}$$

For the range 2000<R<4000 uncertainty exists as to whether flow will be laminar or turbulent (Vennard and Street, 1975). For R>2000, a friction factor of 0.04 was assumed in this review which is consistent with Van der Kamp (1976).

The envelope defining the maximum amplitude of the oscillation is given by

$$X_{max} = X_0\ exp(-\gamma t) \tag{9}$$

It is reasonable to assume that frictional head loss in the riser pipe can be neglected if $h_w \ll X_{max}$.

Table 1 was produced using equations (6) and (9) and data from DC-14 (Figure A-1 in the document being reviewed) to determine values of h_w and X_{max}, respectively. The calculated values of h_w indicate a head loss from friction greater than the driving head (X_{max}) on the system. This is an impossible situation, possibly resulting from the use of maximum velocities. Another explanation may be that fluid in the riser pipe is compressible so that maximum velocity (and therefore frictional loss) decreases down the pipe column. However, the results indicate that frictional losses are potentially significant in determining the underdamped response.

Table 2 shows similar results determined from data presented for RRL-2 (Figure A-9 in the subject document) and also indicates significant frictional losses.

Van der Kamp developed criteria to evaluate when frictional losses may be neglected. For laminar flow conditions he determined that friction can be neglected if

$$\frac{4\nu}{r_c^2} \ll \gamma \tag{10}$$

where ν is the kinematic viscosity of water. For turbulent flow, the condition is expressed as

$$0.005\ (X_o/r_c) \ll \gamma/w \tag{11}$$

Van der Kamp also gives an approximate expression for Reynolds Number, R, for underdamped well response,

$$R \simeq \frac{2\ w\ X_o\ r_c}{\nu} \tag{12}$$

For the DC-14 case considered previously the Reynolds Number is 12,900 indicating turbulent conditions. Equation 11 results in the expression $0.722 \ll 0.077$ indicating that the criterion is not satisfied and that frictional forces may be important. For the RRL-2 case considered previously, R = 6300 and equation 11 gives the expression $0.252 \ll 0.130$, again indicating that the criterion is not satisfied.

Since laminar flow conditions may have characterized the late time response, equation (10) was evaluated for both test cases. This results in the following expressions; 0.0324 << 0.0171 and 0.0125 << 0.0151 for DC-14 and RRL-2, respectively. In both cases, the criterion is not satisfied, indicating that frictional effects are significant.

It should also be noted that the effective length based on the borehole geometry as calculated by equation (10) in the subject document,

$$L = L_c + \frac{3}{8} L_f \tag{13}$$

in often inconsistent with effective length based on the oscillatory response as given by equation (19) of the document,

$$L = \frac{g}{\gamma^2 + w^2} \tag{14}$$

For instance, using data for hole DC-14 in Figure A-1 of the document, the effective length calculated by the first equation yields 3288 feet whereas that calculated by the second equation yields 649 feet. Van der Kamp pointed out a high degree of consistency between the effective lengths calculated by both equations in his data (see Section 2.0). The lack of consistency in the BWIP data raises questions as to the applicability of the assumed wellbore - aquifer model.

4.2 Effects of Wellbore Compressibility

The Van der Kamp solution assumes that the wellbore-packer system is hydraulically "stiff". This implies that the volume displacement in the riser pipe is exactly equal to the volume of water injected into or withdrawn from the aquifer. However, it is reasonable to expect some degree of wellbore compressibility resulting from the compressibility of water in the fluid column, elastic properties of the packers, and gas bubbles entrapped in the system. In a field example described by Neuzil (1982), observed wellbore compressibility was more than 5 times greater than what could be attributed solely to the compressibility of water.

The possibility exists that water level oscillations observed during some slug tests may be related to compressional and frictional properties of the wellbore. In fact, it is possible to define an underdamped harmonic oscillator base solely on wellbore characteristics (i.e., no flow into or out of the borehole). In this physical system, wellbore compressibility operates as a hydraulic "spring" and oscillations of the fluid column are damped out by frictional head losses in the riser pipe. Since this physical model assumes no flow in the aquifer, the predicted harmonic response is independent of aquifer properties. The wellbore model would therefore predict an underdamped response even for the case of an aquifer with zero transmissivity.

Under appropriate conditions, it is conceivable for an underdamped response to be related to both hydraulic properties of the aquifer and compressional/frictional properties of the wellbore. In highly transmissive aquifers, wellbore characteristics probably play a minor role in determining the overall response. However, as aquifer transmissivity decreases, the underdamped response may become dominated by wellbore characteristics. In a relatively tight formation, sole use of the Van der Kamp method to analyze an underdamped slug test response could lead to a large over-estimation of aquifer transmissivity. It may be possible to modify the Van der Kamp method to account for the effects of wellbore compressibility.

4.3 Additional RHO Analyses Using the Van der Kamp Method

The four test cases presented in the subject document represent a very small sample of the underdamped slug tests observed by RHO. At the July, 1982 NRC/BWIP Workshop, the NRC staff reviewed preliminary test data which contained numerous examples of underdamped responses. This information is summarized in Table 3. It should be noted that tests which meet the RHO criteria described in Section 3 were not selectively chosen. All available test data has been listed since we do not have the information to judge which tests meet all of the criteria (in particular the absence of "complicating features").

The transmissivity values determined by the Van der Kamp method are plotted versus values determined by alternative methods (e.g., single-hole pump tests) in Figure 2. The solid line represents a one-to-one correspondence between values determined by both methods while the dashed lines represents a factor of three difference. Of the twenty-one tests plotted on Figure 2, eleven fall within the factor of three range. However, a number of points fall well outside the range. We do not have the information to determine whether these results can be explained by careful examination or re-analysis of the test data.

The obvious conclusion is that in many cases, the values of transmissivity determined by the Van der Kamp method are significantly different from those determined by other methods and that one must question the validity of the results. Furthermore, in zones where the Van der Kamp method was used exclusively (twelve such zones are indicated in Table 3) it is questionable whether the values of transmissivity are meaningful estimates.

Where alternative testing methods suggest relatively low transmissivities in Figure 2 ($T < 30$ ft^2/day), it is interesting to note that six of eight Van der Kamp values lie well above the 1:1 correlation line. This apparent over-estimation of transmissivity may indicate instances where the underdamped response was dominated by wellbore characteristics. In these cases, sole use of the Van der Kamp method could have led to erroneous conclusions regarding site conditions.

Where alternative testing methods suggest relatively high transmissivity ($T > 30$ f^2/day), ten of thirteen Van der Kamp values are below the 1:1 correlation line. In these cases, frictional head losses in the riser pipe may have caused the Van der Kamp method to underestimate aquifer transmissivity.

5.0 CONCLUSIONS

Review of the subject document indicates that there are potential problems associated with using the Van der Kamp method of analysis for underdamped slug tests at the BWIP site. These include:

1. Frictional head losses within the riser pipe are shown to be significant in the two examples we considered. Thus, a major assumption of the Van der Kamp method, that frictional losses in the riser are negligible, is apparently not valid for the cases considered. The criteria given by Van der Kamp regarding frictional losses also indicate that frictional losses cannot be neglected.

2. An underdamped response can theoretically be observed even with zero formation transmissivity as a result of compressible wellbore storage. In this case, use of the Van der Kamp method would lead to an erroneously high value of transmissivity. The effects of wellbore storage are not accounted for by the method.

Examination of data from twenty-one test intervals indicates that the values of transmissivity determined from the Van der Kamp method may vary significantly from values determined by single-hole pump tests. Of the twenty-one intervals in which alternative tests were available, only eleven yielded values within a factor of three of the values determined by the Van der Kamp method. For intervals in which the Van der Kamp method was used exclusively, it is not possible to determine whether the results are meaningful.

Although the Van der Kamp method may eventually prove to be useful at the BWIP site, we believe that several important theoretical problems exist. Furthermore, the available test data do not indicate that the method produces representative estimates of transmissivity on a consistent basis.

6.0 REFERENCES

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Van der Kamp, G., 1976, Determining Aquifer Transmissivity by Means of Well Response Tests: The Underdamped Case, Water Resources Research, vol. 12, no. 1, pp. 71-77.

Krauss, I., 1977, Determination of the Transmissivity from the Free Water Level Oscillation in Well-Aquifer Systems, Paper presented at the Third International Symposium in Hydrology, August, 1977, Fort Collins, Colorado.

Vennard, J.K. and R.L. Street, 1975, Elementary Fluid Mechanics, John Wiley & Sons, Inc.

Neuzil, C.E., 1982, On Conducting the Modified "Slug" Test in Tight Formations, Water Resources Research, vol. 18, no. 2, pp. 439-441.

TABLE 1

FRICTIONAL LOSS CALCULATIONS FOR HOLE DC-14

wt (rad)	t (s)	Vmax (ft/s)	R	f	hw (ft)	Xmax (ft)
$\pi/2$	7.1	1.18	11,460	.04	33.9	5.33
$3\pi/2$	21.2	.930	9,005	.04	20.99	4.19
$5\pi/2$	35.4	.729	7,063	.04	12.91	3.28
$7\pi/2$	49.5	.573	5,550	.04	7.97	2.58
$9\pi/2$	63.7	.450	4,354	.04	4.91	2.02
$11\pi/2$	77.8	.353	3,421	.04	3.03	1.59
$13\pi/2$	92.0	.263	2,549	.04	1.86	1.25
$15\pi/2$	106.1	.218	2,108	.030	.86	.98
$17\pi/2$	120.3	.171	1,654	.039	.69	.77
$19\pi/2$	134.4	.134	1,300	.049	.54	.60

TABLE 2

FRICTIONAL LOSS CALCULATIONS FOR HOLE RRL-2

wt (rad)	t (s)	Vmax (ft/s)	R	f	hw (ft)	Xmax (ft)
$\pi/2$	13.13	.331	5,149	.040	1.689	2.763
$5\pi/2$	65.67	.146	2,280	.040	.331	1.224
$9\pi/2$	118.20	.065	1,010	.063	.102	.542
$13\pi/2$	170.74	.029	447	.143	.046	.240
$17\pi/2$	223.27	.013	198	.323	.020	.106

TABLE 3

TEST RESULTS FROM JULY, 1982 NRC/BWIP WORKSHOP

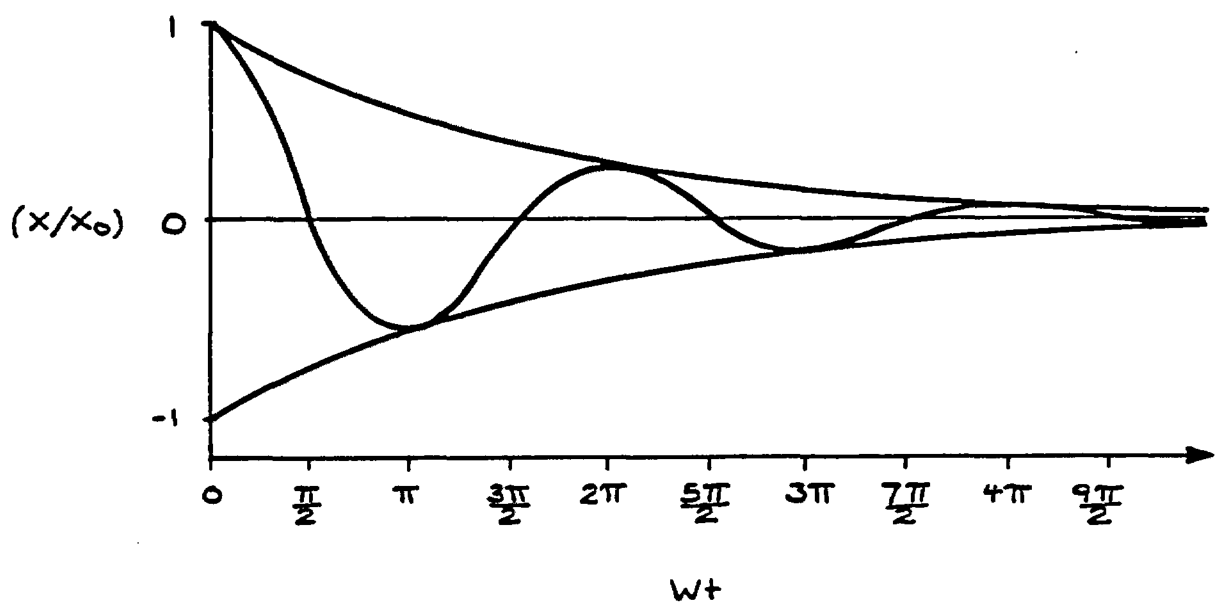
BOREHOLE	DEPTH INTERVAL (ft BGL) TOP	BOTTOM	UNIT	TRANSMISSIVITY (ft^2/d) UNDERDAMPED SLUG TEST	ALTERNATIVE TEST	RATIO COL. 6/COL. 5
DB-15	1045	1105	Roza/ Priest Rpds.	1670	1770	1.06
	1570	1683	French. Spr.	850	714	.84
FORD	650	800	Priest Rpds.	54900	100000	1.82
DC-16	668	835	Rattlesnake Ridge/Pomona	1477	1738	1.18
	1760	1828	Roza	21000	NA	-
	1892	2000	French. Spr.	4300	NA	-
DC-15	4138	4243	Grande Ronde	302	5.1	.017
	3301	3412	Grande Ronde	1092	1.0	.0009
	2961	3113	Grande Ronde	1118	24.8	.022
	2227	2343	Grande Ronde	2192	NA	-
	1540	1593	French. Spr.	1345	NA	-
	1357	1390	Roza	713	NA	-
	1219	1263	Roza/Priest Rpds.	5821	NA	-
DC-12	3341	4070	Grande Ronde	783	NA	-
	4021	4070	Grande Ronde	834	NA	-
	2838	2863	Grande Ronde	590	NA	-
	2818	2843	Grande Ronde	1500	NA	-
DC-6	3530	3824	Grande Ronde	72	111	1.54
	2697	2893	Grande Ronde	6.3	23.4	3.7
McGee	1028	1096	Roza	295	NA	-
DC-14	3260(1)	3335	Grande Ronde	62	67	1.08
	2880	2975	Grande Ronde	0.43	0.24	.56
	2410	2513	Grande Ronde	65	4.2	.065
	1640	1708	French. Spr.	115	97	.84
	1580	1632	French. Spr.	78	334	4.28
	1480	1516	Squaw Creek	125	27	.22
	1285	1346	Roza	319	9340	29.3
	1217	1271	Priest Rpds	1885	NA	-
	1180	1192	Priest Rpds	94	627	6.67
	925	965	Asotin	563	431	.77
	268	475	Elephant Mtn.	2435	4.4	.0018
RRL-2(2)	3247(1)	3344	Cohassett	274-347	830	2.68
	3568(1)	3781	Umtanum	279-596	480	1.13

(1) Test included in Spane, 1983

(2) RRL-2 data was not included in July, 1982 workshop data.
NA indicates alternative tests are not available.

TYPICAL UNDERDAMPED RESPONSE

Figure 1



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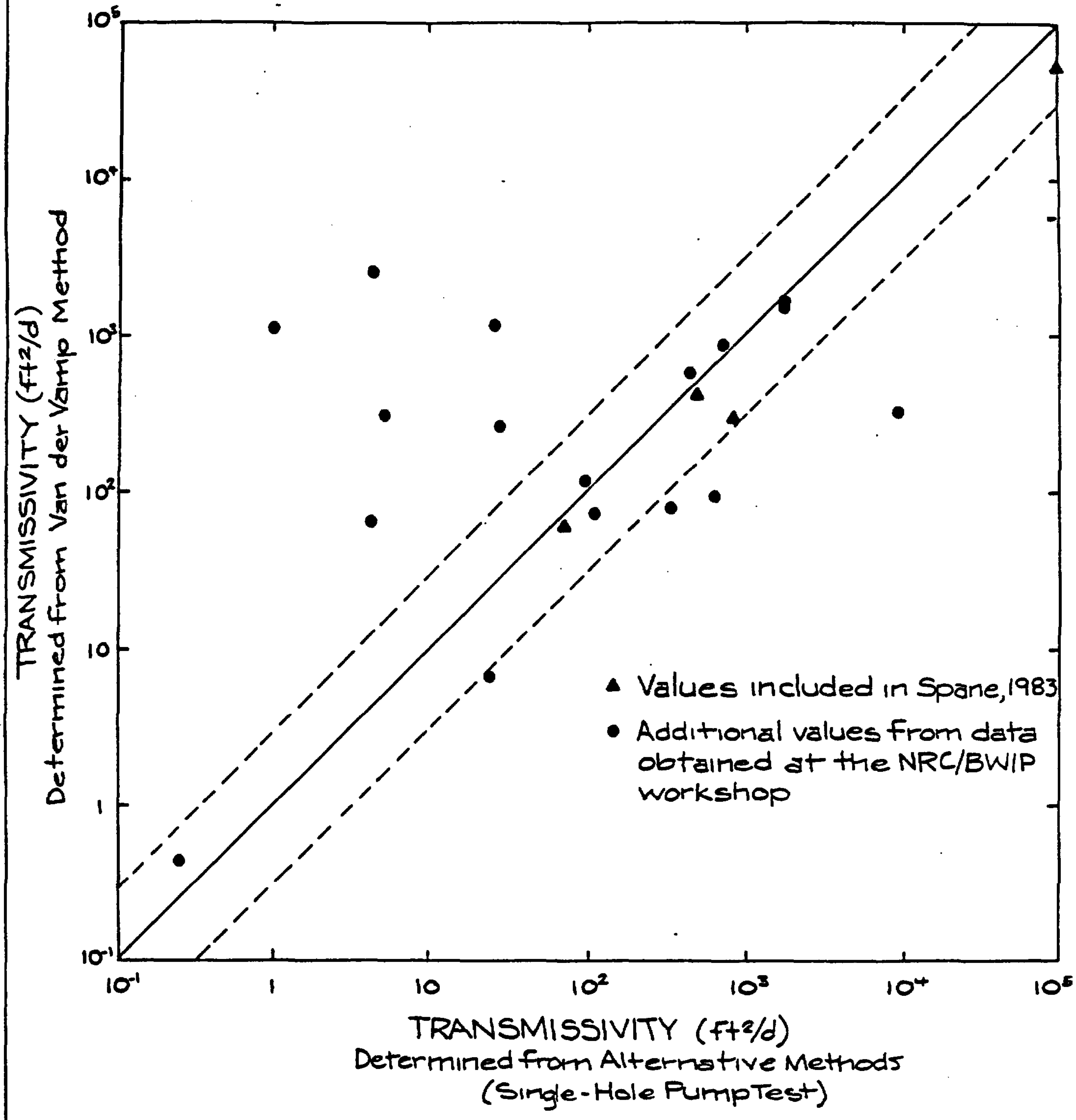
COMPARISON OF TRANSMISSIVITY VALUES CALCULATED FROM UNDERDAMPED SLUG TESTS AND ALTERNATIVE METHODS

Figure 2



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Golder Associates

B7372

ATTACHMENT 3

Review of

APPLICABILITY OF THE VAN DER KAMP METHOD IN SLUG TEST ANALYSIS

by
Williams & Assoc., Inc.

CONCLUSIONS

Dr. Spane's summation of the theoretical basis for the development of the van der Kamp analysis technique is brief but adequate for an introduction to the use of the method. However it is difficult to evaluate without access to the references cited. Two of the references of interest are somewhat obscure and not readily obtainable.

The section on test procedures (p. 5) is too brief. More discussion is necessary concerning the details of the test procedures and equipment installations used at the Hanford site. This observation is particularly relevant to the discussion of the cases cited starting on page 19 and included in Appendix A.

The selectivity of the case history data presented is understood. We recognize the multiphase flow problems encountered with the conventional tests used at the site. However, we note that some data (from borehole RRL-14 in particular) were not noted that could provide some useful insight in the review.

The report does not present convincing evidence that the van der Kamp method is applicable to the test conditions at the Hanford site. We concur with the conclusion that this methodology should be used only as a corroborative method for other tests and analyses procedures (presumably multiple well tests). This conclusion is especially relevant regarding long duration, constant rate or constant drawdown tests and analyses.

PRESENTATION

The terms or parameters for the equations are not always defined. The terms should be defined for clarity. For instance, is the w in equation 16 the w or w' defined previously; is this the damped or undamped oscillatory frequency?

Two references are obscure; the papers were presented at symposia for which copies are difficult to obtain. These references are Krauss, I., 1977 and Shinohara, K. and Ramey, H. J., 1979. There is certainly nothing wrong with using these references but it would be helpful, under the circumstances, to include copies of these papers for the NRC review.

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TEST METHODS

The discussion of test procedures is not sufficiently comprehensive to answer certain fundamental questions concerning the apparatus installed in the borehole and the methods used to produce the pulse. Are the boreholes packed off at the top of the water column in the borehole; or are the boreholes left open to the atmosphere with a transducer located below the water surface? Are the transducers located at the bottom of the hole near the test interval or near the surface of the water column in the borehole? What is the time element involved in creating the pulse? The pulse is not instantaneous in a theoretical sense although the pulse may be in a practical sense. The answers to these questions may be relevant to the resolution of the applicability of the van der Kamp method to the Hanford site.

The description of the analytical procedure and assumptions does not mention the variability of the viscosity in the borehole. The viscosity varies due to the thermal gradient present at the Hanford site; the groundwater temperatures range between 16.3 and 56.6° Celsius (U. S. Dept. of Energy, November 1982, p. 5.1-104 & 5.1-130). Consequently kinematic viscosity varies between 1.10 and 0.50 centistokes. The report should state whether these viscosity variations are significant or not.

The report under review indicates that "approximately 30% of all basalt interflow zones tested by BWIP on the Hanford site exhibit an under-damped response for slug tests" and that the under-damped response occurs most frequently within the Wanapum (p. 19). This predominant response in the Wanapum should be evaluated in greater detail. Is this response due to the depth or length of water filled tubing in the borehole? Is the transmissivity in the Wanapum in direct correlation with this under-damped response?

We would like to have seen references to the recent tests conducted in RRL-14. The preliminary data, reviewed during the July 1983 workshop, for this borehole indicate an anomalous response to a pulse test. The test on the interval between 3294-3403 feet (Cohassett bottom) had two different responses to a pulse depending upon where the transducer was located. The test with the transducer located at the top of the hole responded with a van der Kamp type response. The test with a transducer near the bottom of the hole displayed the conventional exponential decay type response to the pulse. Unfortunately, these were separate tests with pulses of different magnitudes applied to the system.

The report under review notes that an oscillatory type response occurs due primarily to the inertia of the water column in the tubing. This response is said to be especially evident for test intervals exhibiting high transmissivities or for test systems which have large masses of water (p. 12). We question whether this statement indicates the method has limited applicability at the Hanford site because of low transmissivity values and long borehole volumes.

We have been concerned that the oscillatory pressure response to a pulse is merely a tubing phenomenon (water hammer). A simple calculation is possible which indicates the approximate pressure wave velocity. Travel time can be calculated with the assumption that the pressure wave is generated at the top of the water column. The pressure wave is then reflected back from the test interval at some depth within the borehole. We calculated the pressure wave velocity based on the equation:

$$c = (E_v/\rho)^{1/2}$$

where c = velocity of pressure wave,
E_v = bulk elasticity of water,
ρ = mass density of water (Roberson & Crowe, 1975, p. 163).

The pressure wave velocity is approximately 4,870 ft/sec based on a mass density of 1.94 slugs/ft^3 and a bulk elasticity of 3.2×10^5 psi. The mass density of water ranges between 1.94 and 1.92 slugs/ft^3 for water temperatures of 70° and 120° Fahrenheit respectively. The approximate travel time for a pressure wave to travel from the source of the pulse to the test interval (3,260 ft.) and back is 1.3 seconds for borehole DC-14. This is a flowing borehole, therefore the test interval depth is the length of water column in the borehole. The period of oscillation was 28 seconds for the tests reported in the document under review. This analysis shows that the oscillatory behavior does not appear to be merely water hammer in the test tubing.

The Reynolds number (N_R) for the tests reported in the document under review were calculated and are noted below. We calculated these values based on equation 43 in van der Kamp's article (van der Kamp, 1976, p.76). These values are based on kinematic viscosities (v) which vary as noted.

Borehole	Temp. (C°)	v	N_R
DC-14	32a	0.84×10^{-6}	13,300
"	"	"	19,700
RRL-2	53.7	0.57×10^{-6}	8,800
"	"	"	14,700
"	56.6	0.55×10^{-6}	9,900
"	"	"	5,400
Ford	27b	0.92×10^{-6}	22,000

a=average temperature in borehole under static conditions
b=estimated from borehole DB-11 (SCR, Nov. 1982, p.5.1-119)

The Reynold's numbers shown above indicate that turbulent flow conditions existed during these tests. This condition was noted in the report under review (p. 26). The report indicates without verifying reasoning that the turbulence has dissipated after the first oscillation period (p. 26). We believe that turbulence should be discussed in greater detail in the report under review.

Figure 8 of the document under review (p. 21) shows that the van der Kamp method should yield no values of transmissivity below a threshold limit of 10^2 ft^2/day on the Hanford site for the conditions specified by Dr. Spane. We plotted the actual transmissivities determined from the van der Kamp method versus the approximate length of the water filled tubing on Figure 1 (modified from Rockwell's Figure 8). We obtained these data during the July 1982 workshop held in Richland, Washington. We obtained 7 transmissivity values out of a total of 35 that were calculated based upon an under-damped water level response (van der Kamp mehtod) that plot in the over-damped (wrong) region of Figure 1. We also plotted on Figure 2 17 of the 45 transmissivities obtained at the workshop that were determined using the over-damped water level response method. Seven of these transmissivity values calculated based on an over-damped response fall in the under-damped (wrong) region of this figure. Twenty-eight of the transmissivity values obtained at the workshop could not be plotted on Figure 2 since these transmissivity values were less than 10^1 ft^2/day. These values, if plotted, would fall in the correct portion of the graph. We believe that this figure exemplifies the uncertainty of this technique.

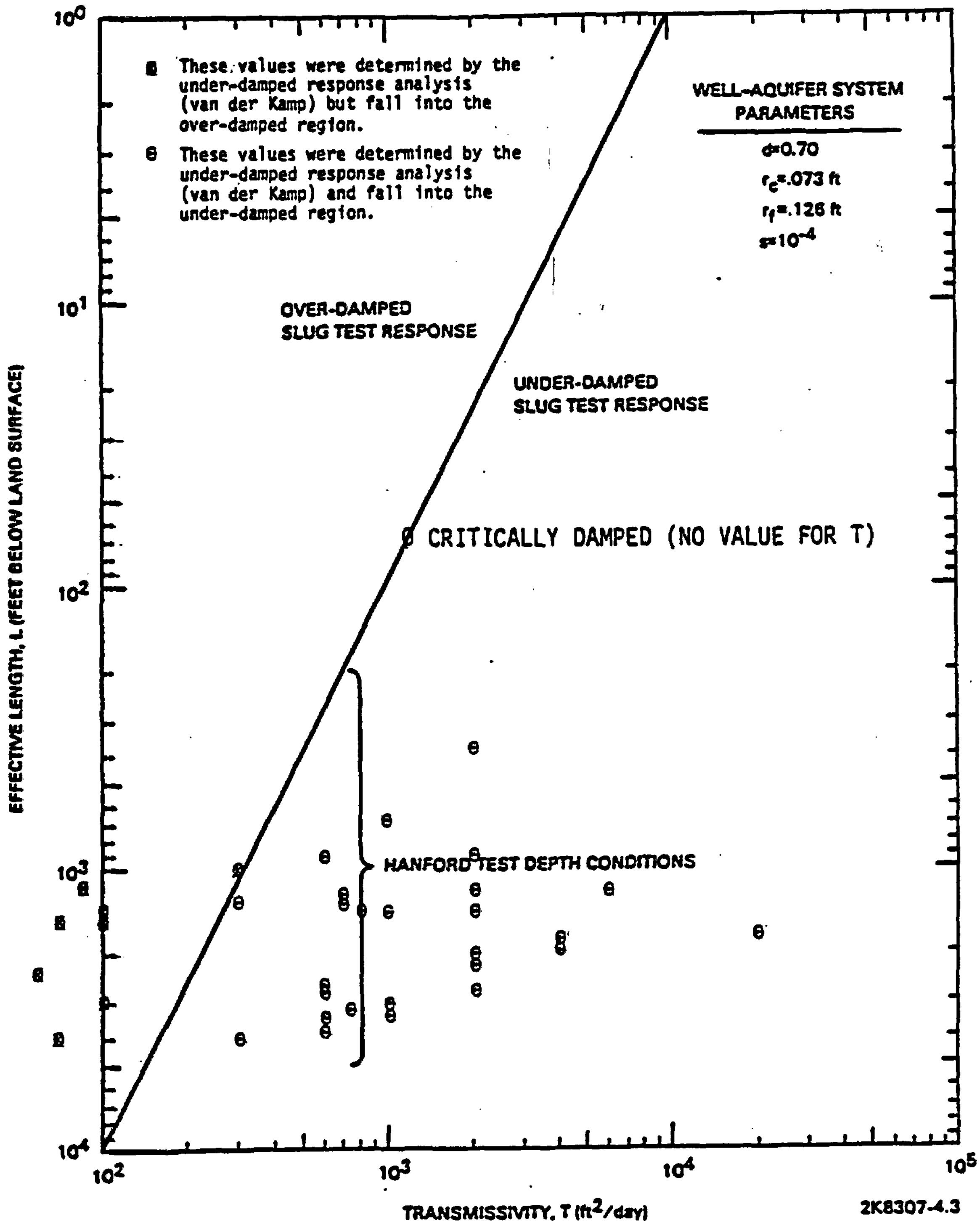

FIGURE 1. Expected Well Response Behavior for Slug Tests Conducted Under Common Hanford Test Conditions. (Figure 8)

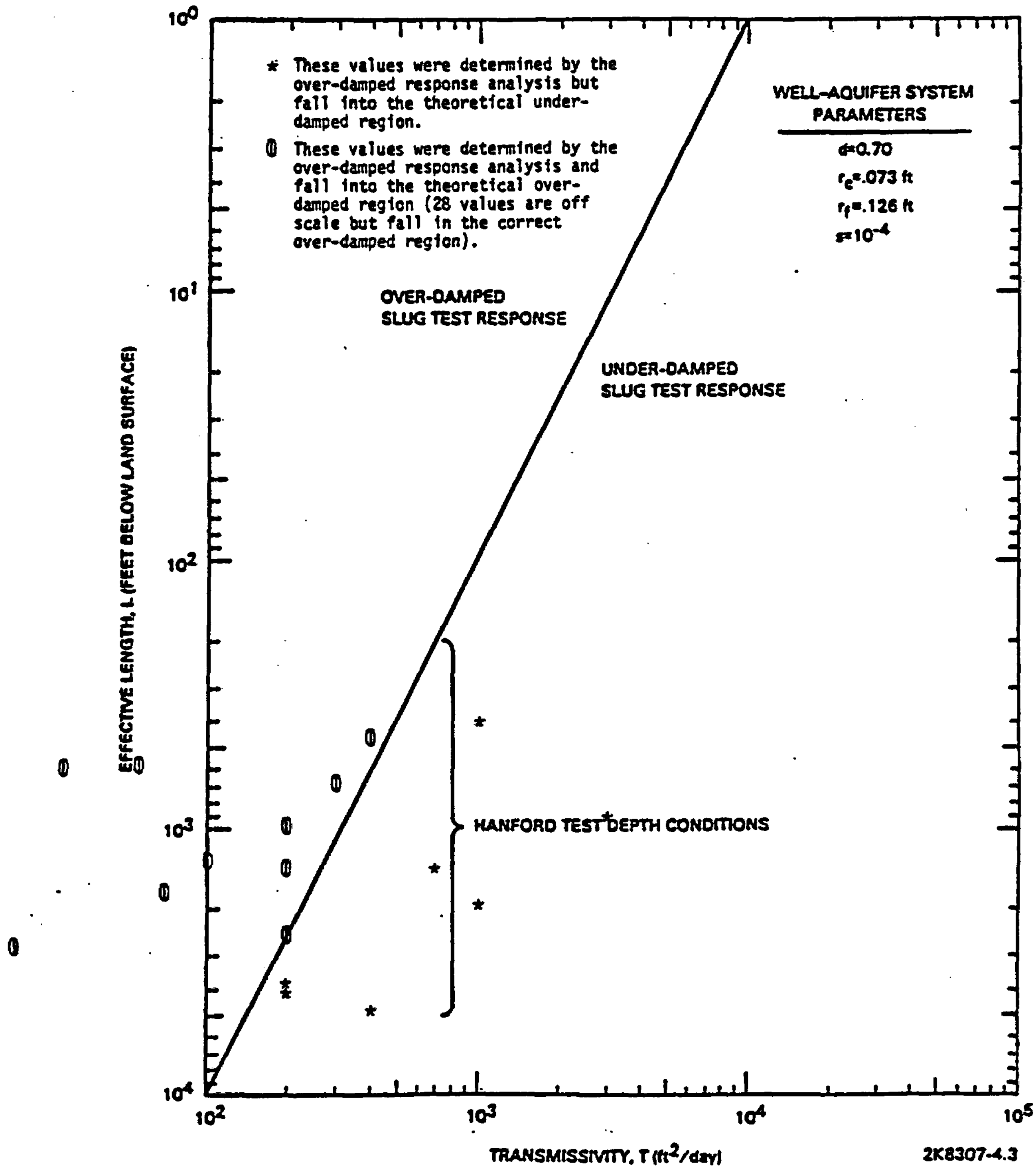

FIGURE 2. Expected Well Response Behavior for Slug Tests Conducted Under Common Hanford Test Conditions. (Figure 8)

Selected References

Roberson, J. A. and Crowe, C. T., 1975. Engineering Fluid Mechanics. Houghton Mifflin Co., Boston, Ma. 520 p.

U. S. Dept. of Energy, November 1982. Site Characterization Report for the Basalt Waste Isolation Project. DOE/RL 82-3, 3 volumes.

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