

Analysis and Interpretation of a Recirculating Tracer Experiment

Performed on a Deep Basalt Flow Top

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ABSTRACT

Artificial tracer experiments are generally considered to be the most direct methods available for evaluating groundwater flow and solute transport parameters. Experimental data generated from tracer tests can serve as input to solute transport models that reconstruct or predict groundwater flow system behavior or response. Such experiments have been carried out within the Columbia River basalts in south-central Washington State. The

results of these experiments, while successful in terms of obtaining numerical estimates of the targeted parameters (effective thickness and dispersivity), also provided information to the general mechanics of basalt aquifers. Initial experiments were performed within a basalt flow top, approximately 3,450 feet (1,050 meters) below land surface, using paired boreholes separated by about 55 feet (16.7 meters) at depth.

Transmissivity of the flow top was estimated to be 0.7 square feet per day (0.07 square meters per day), and storativity was about 3×10^{-5} . The tracer testing provided estimates of longitudinal dispersivity in the range of 1.5 to 2.8 feet (0.46 to 0.84 meter) and effective thicknesses between 0.006 and 0.01 foot (0.002 and 0.003 meter). Testing procedures involved closed-loop recirculation of the tracer while both monitoring in real time and sampling over discrete time intervals.

Corroborative results were obtained from two individual experiments using iodine-131, and potassium thiocyanate (KSCN) tracers, respectively. Data reduction and interpretation involved type-curve matching. The type curves were specially developed to account for either single- or distributed-pulse inputs of the tracer into the formation. This aspect provided a means of evaluating the degree of tracer dispersion that can occur during transport from the surface to the test interval. Analysis of cation species collected during the KSCN tracer test

also provided important information about tracer dynamics within the groundwater system.

INTRODUCTION

Artificial tracer experiments have been described as the most direct method available for assessing groundwater velocities (Freeze and Cherry, 1979). While these experiments can determine the average groundwater velocity between two points in a flow system, problems can arise when tracer-experiment data are used to make parameter estimates in order to model the flow system on a scale different from that of the experiment.

This paper describes the design, results, and analysis of two recirculating groundwater tracer experiments performed on a deep basalt flow top within the Columbia River Basalt Group at the U.S. Department of Energy-controlled Hanford Site in south-central Washington (Fig. 1). The experiments were performed in December 1979 and January 1982. The results of these experiments were generally successful in that numerical values for the targeted parameters were generated. Further evaluation of the experimental results provided some additional insights into the uncertainties associated with tracer testing and a better conceptual understanding of groundwater hydraulics of basalt flow tops. This information is considered to be important to the eventual application of the data as well as in the design of future hydrologic tests. Because the two tracer experiments were

conducted in a similar manner, the discussions focus primarily on the latter test with which the authors are more familiar. However, noteworthy differences are described in the text where appropriate. Additional details regarding the earlier tracer experiment may be found in the appendix of a report by Gelhar (1982).

The test site, known as DC-7/8 (see Fig. 1), is situated within the southeastern portion of the Cold Creek synclinal structure described in detail in Myers and Price (1981). The syncline is in the Pasco Basin which, in turn, occupies the centralmost portion of the Columbia Plateau (see Thornbury, 1965). Land surface elevation at the site is approximately 545 ft (166.2 m) above mean sea level (MSL). Surficial geology of the site includes late Cenozoic sediments of the Hanford Formation and Ringold Formation. Boreholes DC-7/8 penetrate the top of the Columbia River Basalt Group at about 702 ft (214.0 m) below land surface (BLS) or an elevation of 157 ft (47.9 m) below MSL. Three formations of the Columbia River Basalt Group are present at the test site: Grande Ronde, Wanapum, and Saddle Mountains Basalts. Various members of the sedimentary Ellensburg Formation are interbedded among, primarily, the upper basalt flows. As illustrated in Figure 2, the basalt stratigraphy represents a sequence of at least 80 distinct layers.

TEST HORIZON

The horizon selected for tracer testing is the McCoy Canyon flow top (see Fig. 2 and 3). The general lithologic character of this horizon can be described as a high porosity zone within the Grande Ronde Basalt between 3,422 and 3,459 ft (1,043.0 and 1,055.0 m) BLS. Core data indicate that the flow top consists of a (nontectonic) brecciated zone with altered clasts of vesicular and nonvesicular basalt cemented by basalt and secondary minerals. In places where the brecciated material is most weakly cemented, thin, rubbly zones are present. It is believed that, at this site, the basalt flow tops represent the primary zones of lateral hydraulic conductivity within the basalts. The flow top is physically bounded above and below by much denser basalt occupying the interior portion of individual flows. The flow interiors are characterized by a system of vertical-to-fanning, primary fractures or joints formed by shrinkage of the original molten rock mass as it cooled. Most of these joints are filled with secondary minerals and are hydraulically tight. The dense interior portions of these flows are believed to function primarily as confining horizons with respect to the flow tops (LaSala and Doty, 1971; LaSala et al., 1973; Luzier and Burt, 1974; Gephart et al., 1979; U.S. Department of Energy, 1982; Gephart et al., 1983; Newcomb, 1982).

Interval Isolation

Boreholes DC-7/8 are paired boreholes situated a nominal distance of 55 ft (16.7 m) apart at the test interval. Borehole DC-7 was rotary drilled at a diameter of 8-5/8 in. (3.40 cm). Borehole DC-8 is an NX-type core hole (approximately 3 in. (1.2 cm) in diameter). Both holes are cased across the Vantage interbed and open (uncased) within the Grande Ronde Basalt (see Fig. 2 for stratigraphy). Because DC-7/8 extend considerably deeper than the McCoy Canyon flow, it was necessary to utilize a packer system that would provide isolation both above and below the test interval (flow top). To achieve this, a water-inflatable straddle-type packer system was used. The straddle interval in DC-7 was 67.4 ft (20.5 m) in length, from 3,410.2 to 3,477.6 ft (1,039.7 to 1,060.2 m) BLS and 73.4 ft (22.4 m) in length, from 3,407.0 to 3,480.4 ft (1,038.7 to 1,061.1 m) BLS in DC-8.

The effective or contributing test interval within this zone was known to be considerably shorter than the straddle interval. Analyses of core data and geophysical logs, for example, showed that the flow top exhibited a highly porous texture across a zone some 37 ft (11.3 m) thick. The primary zone of lateral hydraulic conductivity, which was believed to occupy the rubbly horizon mentioned earlier, was probably even thinner.

The distance between boreholes, as ascertained from gyroscopic surveys, ranged from 54.9 to 55.4 ft (16.7 to 16.9 m) over the straddle interval, and was 55.1 ft (16.8 m) at the midpoint of the test horizon. In addition to the straddle packers, water-inflatable bridge plugs, set about 150 ft (35.7 m) below the lower straddle packer, provided additional ability to monitor for vertical leakage within the boreholes. All packers were set within the dense interior portions of the McCoy Canyon and overlying flows in order to achieve proper seating and compliance. The triple-probe pressure transducers enabled the monitoring of possible leakage above and below the straddle due to packer deflation during the testing. This configuration as well as some details regarding equipment specifications is depicted in Figure 4.

Hydrologic Testing and Parameter Estimates

Characterization of the McCoy Canyon flow top at DC-7/8 began with a series of hydrologic tests to ascertain general hydraulic properties of the zones. The observed prepumping water level within the test horizon was approximately 139 ft (42.4 m) BLS. Testing was initiated with constant pumping at a rate of about 1 gal/min (3.8 L/min) at DC-7 using a submersible pump as shown in Figure 4. Initially, a long-term constant discharge test was planned, but, due to excessive drawdown at DC-7, the

test was terminated after 402 min of pumping. Following pumping, water-level recovery was monitored for about one week.

Analyses of the test drawdown and recovery data were performed by Rockwell Hanford Operations as well as Lawrence Berkeley Laboratory staff using analytical techniques developed by Theis (1935), Cooper and Jacob (1946), Hantush (1960), Papadopoulos and Cooper (1967), and Agarwal et al. (1970). The obtained estimates of transmissivity fell in the range of 0.4 to 0.85 ft²/day (0.04 to 0.079 m²/day). The value of 0.7 ft²/day (0.065 m²/day) was taken as the best estimate. Based on the drawdown analyses, estimates of storativity ranged between 1.1×10^{-5} to 4.1×10^{-5} . The value of 3×10^{-5} was taken as the best estimate of storativity. Assuming homogeneity throughout the 37-ft (11.3-m) flow top thickness, the values of equivalent hydraulic conductivity and specific storage corresponding to these best estimates of transmissivity and specific storage are 0.01 ft/day (3×10^{-3} m/day) and 8×10^{-7} /ft (2.4×10^{-7} /m), respectively.

Hydrochemistry

The hydrochemical properties of composite Grande Ronde groundwater samples taken from borehole DC-7 are similar to those of other Grande Ronde waters within the western portion of the Hanford Site. The dominant cation is sodium (Na⁺), and the dominant anions are chloride (Cl⁻) and sulfate (SO₄⁼). A listing

of data comparison on major constituents within a composite sample taken from DC-7 is provided in Table 1. For comparison, the average Grande Ronde water composition for all samples taken at the Hanford Site is also given.

TRACER TESTING

The following paragraphs provide details regarding the field testing configuration, procedure, results, and analyses in conjunction with testing the McCoy Canyon flow top at the Hanford Site.

Testing Configuration

The recirculating test configuration (sometimes referred to as the doublet or two-well test) results in a hydraulic potential field analogous to the familiar electromagnetic dipole and is treated mathematically as a coupled source-sink problem (see Jacob, 1950; Carslaw and Jaeger, 1959; DaCosta and Bennett, 1960; and Muskat, 1982). The principal aspects of this flow regime are that, within relatively homogeneous and isotropic media, the hydraulic gradients between recharging and discharging wells are effectively maximized.

The field design and other aspects of the hydraulics of the two-well recirculating configuration have been treated by Webster et al. (1970), Grove and Beetem (1971), and Thompson (1980). A schematic of the field configuration used at the DC-7/8 site during the more recent test at DC-7/8 is shown in Figure 5.

During testing, water was withdrawn from DC-7 using a submersible pump. At the wellhead, the water was routed through a 5- μ m filtration system (to prevent clogging of the injection well) and flow totalizer before entering a return line to the injection well DC-8. A near-constant flow rate was maintained by an in-line flow regulator. As shown in Figure 5, a small sample split was made immediately downline from the controller. This was achieved by means of a metering pump that maintained a near-continuous flow 0.02 gal/min (about 5 mL/min) to the tracer-detection apparatus. During the test, downhole pressures were monitored above, within, and below the test interval by means of a triple-pressure probe. Environmental conditions at the wellhead were maintained by a portable enclosure, which also housed onsite analytical and testing equipment.

Test Procedure

A systematic series of field trials was performed to determine an optimal rate of groundwater circulation. The objective of this procedure was to find a circulation rate that would most closely emulate a steady-state balance with respect to the drawdown and impression at DC-7 and DC-8, respectively. These trials showed that, at an essentially constant rate of 1 gal/min (3.8 L/min), the water could be pumped from DC-7 and recirculated in a closed loop to DC-8 in equal volumes (i.e., the discharge rate at DC-7 is equal to the recharge rate at DC-8). This

circulation was maintained and monitored for about 2 days, whereupon the drawdown at DC-7 stabilized at about 77 ft (23.5 m) and the groundwater mound at DC-8 built up 2 ft (0.6 m), both in reference to the original static levels. The apparent hydraulic gradient between DC-7 and DC-8 induced by this regime was about 1.4 (vertical/horizontal) or approximately 1,000 to 10,000 times the ambient gradient. It is emphasized, however, that due to thermal mixing that occurred during the discharging and recharging in the boreholes, the true hydraulic gradient (as an expression of potential) cannot be ascertained from water level data alone. During this period of circulation, analytical and other onsite equipment were tested and calibrated.

The tracer test was initiated by rapidly pouring 1 gal (3.8 L) of aqueous potassium thiocyanate (92,470 p/m KSCN) into the open surface tubing at DC-8. This tracer was selected on the basis of its low background concentration, detectability using ultraviolet (UV) absorption methods, and conservative (non-sorbing) properties (Davis et al., 1980). Following injection, the tracer was carried downward some 3,000 ft (900 m) through the tubing. Upon reaching the test interval, it dispersed into the open borehole through ports within the mandrel and, subsequently, into the basalt flow top. Tracer dynamics were monitored continuously using a UV absorption detector calibrated to a

wavelength of 205 nm. Additionally, time-integrated samples were collected over discrete intervals for eventual laboratory verification.

The only noteworthy differences between this tracer test and the earlier test were the tracers and the detection methods. In the earlier test, a frozen, water soluble iodine-131 (47.0 mCi) tracer was used, and this was detected by means of a gamma radiation counter at the DC-7 well head. In addition, flow rates in the earlier test varied between 2 and 3.5 gal/min (7.5 and 13 L/min) and only about two-thirds of the water discharged at DC-7 was reinjected into DC-8.

For a general account of the several groundwater tracer material groupings as well as their applicability under various experimental situations, see Davis et al. (1980).

Testing Results

The time-concentration response of the primary (SCN^-) and secondary (K^+ and Na^+) tracers observed at the detection point during the passage of the first peak is shown in Figure 6. While Na^+ was not injected with the anion, its breakthrough mimics that of K^+ , indicating cation exchange along the flow path. The concentrations are those measured from the time-integrated samples collected during testing. In general, SCN^- is considered to be a conservative (non-sorbing) tracer whereas K^+ and Na^+ , owing primarily to their positive valences, are less

conservative. Thus, the manner in which the dynamics of these less conservative tracers mimic those of the SCN^- is noteworthy.

At approximately 1,250 min following the tracer injection, breakthrough was observed at the detection point. At about 1,420 min, 170 min following breakthrough, the peak SCN^- concentration (about 130 p/m) was observed. A second breakthrough, due to recirculation of the original tracer mass back into the test interval, began at about 2,570 min. Due to equipment problems, sampling occurred less frequently during the latter portion of the test. The test was terminated 3,240 min after injection. While the continuous UV monitor provided an important capability for monitoring tracer dynamics during the testing, reliable quantitative data could not be extracted from the flowthrough detector log due to a loss of linearity in the output signal.

Analytical Methodology

Analysis of the data from the tracer test was performed by means of type-curves developed by Gelhar (1982) after the general theory introduced by Gelhar and Collins (1971). Tracer concentration as a function of space and time is given by:

$$c(s,t) = \frac{m}{u(s_0)\sqrt{4\pi\alpha\omega}} \exp\left[-\eta^2/4\alpha\omega\right] \quad \text{Eq. 1}$$

where:

c = concentration

s = distance from the injection well along a streamline

t = time

α = longitudinal dispersivity

$\eta = \tau(s) - t$

$\tau(s) = \int_{s_0}^s ds/u(s)$, traveltime to s

$\omega(t) = \int_{s_0}^{\bar{s}} ds/ u(s)^2$

$\bar{s}(t)$ = mean location of the pulse at time, t

$u(s)$ = seepage velocity

m = mass of tracer per net area of aquifer injected at
 $s=s_0$ at time $t=t_0$.

Equation 1 describes the tracer concentration along streamlines between the recharge and pumping wells when an instantaneous pulse (slug) of conservative tracer is introduced in the recharge well. This equation is applied along each streamline identified by the value of the stream function (ψ). Therefore, the velocity, u , depends on ψ and as a result, on $\tau(s, \psi)$ and $\omega(t, \psi)$. The coefficient, $m/u(s_0)$ in Equation 1 is evaluated by noting that at the recharge well

$$u(s_0) = Q_r / (2 r_w n_F H) \quad \text{Eq. 2}$$

where:

Q_r = recharge rate

r_w = well radius

n_F = effective porosity

H = aquifer thickness

$$m = M/(2\pi r_w n_F H)$$

M = mass of tracer injected

and, thus,

$$m/u(s_o) = M/Q_r$$

The concentration at the pumping well (c_w) is found by calculating the flow-weighted concentration as the following integral:

$$c_w = \frac{2H}{Q} \int_{\psi=0}^{Q/2H} \left(\frac{M}{\beta Q}\right) (4\pi\alpha\omega)^{-\frac{1}{2}} \exp[-(\tau-t)^2/4\pi\omega] d\psi \quad \text{Eq. 3}$$

where:

$$\beta = Q_r/Q$$

Q = discharge rate

In this integral, the flow integrals, τ and ω , depend on the stream function, ψ . These flow integrals can be evaluated by either analytical or graphical techniques. The family of dimensionless type curves shown in Figure 7 for selected values of ϵ (where $\epsilon = \alpha/L$, and L = borehole spacing) were generated using numerical techniques.

A different technique was initially used to analyze the data for the December 1979 test. This technique involved a two-point match based on time-to-peak and time-to-half-peak concentrations. Gelhar (1982) contains a detailed development of the mathematics involved with the two-point method. The results of the

iodine-131 test have since been reanalyzed using the curve-matching technique. This analysis showed that the results of the two analytical methodologies were comparable (i.e., within less than $\frac{1}{2}$ order of magnitude for $n_F H$ and α). Despite the relatively close agreement between the simpler two-point results and the type curve solution, the type curve methodology is considered to be a more precise solution because it attempts to utilize the entire time-concentration distribution of the tracer, as opposed to only two of its values.

Data Analysis and Results

The primary measurements that are performed during the recirculating tracer test are the time-tracer concentration ($c(s,t)$) observed at the discharge well and the circulation rate (Q). Using the methodology described above, the time-tracer distribution can be used to obtain estimates of longitudinal dispersivity (α) and effective thickness ($n_F H$) of the test interval. These parameters, in turn, are essential to interpreting the flow and transport characteristics of the porous medium.

The best fit obtained between the test data (time- SCN^- distribution) and the type curves developed by Gelhar (1982) is illustrated in Figure 8. This fit was obtained by means of an

iterative BASIC code that allowed the operator to select and analyze the fit with respect to the following:

- Least-squares error between the type curve and observed data
- Analytically-determined estimates of the "lag-time" (a parameter used to correct for the borehole and tubing residence time of the tracer)
- Minimizing the difference between the mass of SCN^- injected and the theoretical mass recovery projected.

The ϵ value corresponding to the curve fit is 0.05. Knowing that the best-fit is obtained from this ϵ value and the value for the spacing between the test boreholes (L), an α value can easily be obtained from the definitions given after Equation 3, and the equation

$$\hat{T} = Qt/\eta_F HL^2 \quad \text{Eq. 4}$$

can be used with the match point value for dimensionless time (\hat{T}) obtained from the fit to estimate $\eta_F H$. Alternatively, $\eta_F H$ can also be obtained from the dimensionless concentration (C) of the match point using the following equation:

$$c = \eta_F HL^2 C_w / M \quad \text{Eq. 5}$$

The estimates of α and $\eta_F H$ thus obtained, using a borehole spacing (L) of 55.1 ft (16.8 m) and a circulation rate (Q) of

1 gal/min (3.8 L/min), are 2.76 ft and 0.006 ft (0.84 m and 0.002 m), respectively.

In general, the fit shown on Figure 8 appears to be quite good with the possible exception of the late-time data where the type curve tends to systematically overestimate. The type-curve fit is not applicable to the second breakthrough, which is represented by the late-time data shown on Figure 8. It should also be noted that the late-time sampling frequency was insufficient to resolve the magnitude of the second peak. Therefore, the data shown on Figure 8 represent only a portion of the second breakthrough curve.

EVALUATION AND DISCUSSION

In any experiment of this type, developing a proper understanding and interpretation of the significance, representativeness, associated uncertainties, and possible application of the results obtained is equally as important as obtaining numerical estimates of the targeted parameters. To a significant degree, one must exercise the methods of scientific inquiry in meeting this challenge. This fact implies a utilization of any available lines of evidence that might assist in the final interpretation of the experiment as well as a resolution of the need for additional data and recommendations for the best method(s) for their acquisition. A discussion of the extent to which this exercise has been carried out with

regard to the particular experiments at DC-7/8 follows. It is hoped that this type of analysis and inquiry serves as a useful example for other investigators engaged in either the design and execution of the field experiment or the ultimate interpretation and application of the experimental results.

In particular, the parameter estimates obtained from the testing should be evaluated both in terms of how they compare with other values reported in the literature and their apparent reasonableness for the specific conditions of the test site. For the DC-7/8 test, the estimates of dispersivity and effective thickness may be compared in this fashion as well. Data on the chemical dynamics of the tracer may be used to provide an additional dimension to the interpretation.

Dispersivity

Dispersivity is a property of porous media that attempts to account for the degree of hydromechanical mixing of solutes that occur longitudinal and/or transverse to the groundwater flow path. Investigators of solute transport phenomena have, in recent years, given considerable attention to a phenomenon associated with field experiments known as dispersion scale dependency. Certain of these investigators have noted that apparent scale dependency can be related to the factors introduced by the experimental configuration. For example, Pickens and Grisak (1981) suggested that misinterpretation of

dispersion scale dependency can result if the converging and/or diverging effects of streamlines are not accounted for properly. Others (e.g., Domenico and Robbins, 1984) have noted that misinterpretations of scale effects can arise if the multidimensional character of the dispersion problem is not accounted for properly in the analysis.

Focusing on the physical basis for dispersion phenomena, several investigators (e.g., Gelhar et al., 1979; Matheron and de Marsily, 1980; Dagan, 1982; Gelhar and Axness, 1983) have demonstrated that large, field-scale dispersion phenomena are related primarily to formation heterogeneities and can increase with displacement distance. Gelhar et al. (1979) suggest two possible explanations for dispersion scale dependency:

- Spatial variation of hydraulic conductivity in the porous medium
- Measurement scale.

The scale of a field experiment becomes important because, in general, large solute displacements are required before the "asymptotic macrodispersivity" is developed (Gelhar et al., 1979; Gelhar and Axness, 1983). Asymptotic macrodispersivity is an invariant parameter for a given porous medium. It is the correct dispersivity to use for solute transport modeling on any scale larger than the scale required for its development. Any dispersivities determined on a smaller scale will be smaller than

the asymptotic macrodispersivity, and will strictly be representative only of local dispersion phenomena.

The dispersivity estimates for the Hanford basalts obtained from the DC-7/8 tests ranged between 1.5 and 2.8 ft (0.46 and 0.84 m), corresponding to ϵ values between 0.03 and 0.05. The magnitude of these values in relation to the displacement distance, 55.1 ft (16.8 m), can be compared to other field-determined dispersivities summarized by Lallemand-Barres and Peaudecerf (1979) as shown on Figure 9. On Figure 9, the DC-7/8 test results can be favorably compared with the general scaling trend observed in other field-determined dispersivity estimates. This indicates that the estimate obtained for dispersivity of the flow top is probably not representative of a dispersivity required to model regional-scale transport.

Effective Thickness

In consideration of the relationship between porosity and dispersivity, Gelhar et al. (1979) suggest that, if porosity and hydraulic conductivity are uncorrelated, the asymptotic macrodispersivity remains unaffected by porosity variations. However, if porosity and hydraulic conductivity are positively correlated, porosity variations will cause a decrease in asymptotic macrodispersivity. While this type of information is generally obscure (depending on the maturity of the investigation of a particular aquifer) the flow dynamics observed during tracer

testing can assist in building a conceptual understanding of the flow mechanics of basalt aquifers, particularly as they relate to the general nature and distribution of porosity within a basalt flow top. Davis (1969), in a general treatise on the factors that determine porosity and permeability of rocks, provides some insight into how porosity might manifest itself in the diagenesis of basalt, and into factors that might regulate permeability anisotropy. It is important to note, however, that Davis's discussion relates primarily to aspects of regional flow and does not necessarily account for the scale examined by these tracer tests. Norton and Knapp (1977) have developed a porosity model for fractured media that may be applicable to the McCoy Canyon flow top. This model is expressed as:

$$n_T = n_F + n_D + n_R \quad \text{Eq. 6}$$

where:

n_T = total porosity

n_F = effective or flow porosity

n_D = diffusion porosity

n_R = residual porosity

Each component represents a discrete type of porosity which may be present within the fractured porous medium. The n_R value represents the fraction of the n_T not connected to n_F or n_D . Clearly, tracer tests, such as those described above, provide primarily estimates of n_F . The roles of diffusion mechanisms

during testing were probably diminished relative to advective transport as a result of the velocities introduced by the imposed gradients.

As evident from observation of the core data for the McCoy Canyon flow top, heterogeneities may play an important role in controlling groundwater movement through the basalts. As described earlier, the flow top is comprised of a 37-ft (11.3-m) thick vesicular zone within which a much thinner zone of poorly consolidated material may represent the effective test zone thickness. Thus, it may be inferred that, although the total porosity (n_T) of the flow top is comparatively high, a large percentage of n_T would be classified as residual porosity (n_R). A corollary to this interpretation is that the zones of higher n_F have correspondingly higher hydraulic conductivities.

A dynamic temperature log run at DC-7/8 subsequent to the tracer testing (after the downhole packers were removed) provides support for the interpretation that the effective test zone for the McCoy Canyon flow top is relatively thin. The fluid-temperature log trace that resulted in DC-8 as a result of pumping groundwater from DC-7 is illustrated in Figure 10. The dynamic temperature log at DC-8 suggests the following:

- Groundwater was moving both downhole and uphole within DC-8 and mixing within a relatively narrow zone at the base of the flow top, approximately 3,456 to 3,473 ft (1,053.7 to 1,058.8 m) BLS.

- The portion of the flow top transmitting the major component of flow could be as thin as 3 ft (1 m) or less, based on the overlap between the zones of high porosity and apparent vertical mixing.
- Additional groundwater transmission (but of a significantly lesser degree than the zone described above) may be occurring across other portions of the flow top based on the minor undulations in the dynamic fluid temperature log as compared with the relatively linear trace observed across the dense interior.
- The apparent rate and volume of groundwater moving uphole was greater than that moving downward, as evidenced by the degree of thermal displacement from static conditions.

While the depth resolution of the dynamic fluid temperature log may be low compared to static logging techniques, qualitatively, the observations made at DC-7/8 are consistent with observations made at other boreholes penetrating the Grande Ronde Basalts at the Hanford Site (e.g., Strait and Spane, 1982). Collectively, these results suggest similarly narrow zones of higher hydraulic conductivity that occupy between 5 and 25% of the flow tops.

A better understanding of the significance of these results with respect to the variation of porosity and permeability within the flow top, can, perhaps, be gained by considering two

hypothetical extremes with regard to the distribution of flow porosity and hydraulic conductivity across the flow top: (1) the horizon is essentially equivalent to a granular porous medium across its entire 37-ft (11.3-m) thickness, and (2) the hydraulic conductivity within the flow top is entirely controlled by a single fracture connecting the two boreholes. To visualize these extremes, consider the two equations:

$$K = \frac{T}{H} \quad \text{Eq. 7}$$

and

$$n_F = \frac{n_F H}{H} \quad \text{Eq. 8}$$

Equation 7 relates the equivalent hydraulic conductivity (K) of the contributing zone to the transmissivity (T) and thickness (H) of the contributing zone. Equation 8 relates the effective or flow porosity (n_F) of the contributing zone to the effective thickness ($n_F H$) and thickness (H) of the contributing zone.

Since T and $n_F H$ are both determined from the analysis of field test data, it is possible to vary H within known physical bounds to illustrate the impact on the derived parameters K and n_F . In the case of the McCoy Canyon flow top at DC-7/8, T is 0.7 ft²/day (7 X 10⁻² m²/day), and $n_F H$ is 6 X 10⁻³ ft (2 X 10⁻³ m).

Figure 11 is a plot of K and n_F versus H for the McCoy Canyon flow top. The bounds on H are the distance between the packers

(37 ft (11.3 m)), and some very small thickness that corresponds to a single smooth fracture having the same transmissivity as the flow top.

The minimum contributing zone thickness would be defined by a single, smooth-walled fracture having a transmissivity equivalent to the transmissivity of the McCoy Canyon flow top. Such a fracture would have an aperture of 3×10^{-4} ft (1×10^{-4} m), a hydraulic conductivity of 2,600 ft/day (790 m/day) and an effective porosity of unity. However, the fact that the effective thickness determined from the tracer test is 6×10^{-3} ft (2×10^{-3} m) would preclude the occurrence of a clean fracture of aperture 3×10^{-4} ft (1×10^{-4} m). In addition, a smooth-walled fracture having an aperture equal to the determined effective thickness (6×10^{-3} ft) (2×10^{-3} m) would have a transmissivity of about 9,000 ft²/day (840 m²/day). This implies that the true minimum contributing zone thickness (H) is a little greater than the effective thickness. Clearly, the range of possible contributing zone thicknesses is very broad.

Tracer Dynamics

The breakthrough curve produced from the SCN^- data is considered to be a rather smooth plot in comparison with the gamma trace obtained during the iodine-131 test. In part, this is attributed to low background of SCN^- and time-integrated sampling.

Although the experiment was not specifically designed to assess chemical partitioning during transport, a qualitative evaluation was made possible by examining the results of analysis for 33 cations performed on the time-integrated samples. These analytical data show distinct cation exchange of K^+ , from the SCN^- salt, for Na^+ , which probably occurred either as a solute within the formation water or was dissolved from solids in the basalt flow top. Significant exchange between other cations was not apparent. These data, as shown earlier on Figure 6, display dynamics that are very similar to the much more conservative SCN^- . Using numerical integration techniques, the mass recovery of each ion up to 2,268 min was evaluated. The results of the mass balance, as shown in Table 2, show a near-complete electrochemical balance between the anion (SCN^-) and the cations (K^+ plus Na^+).

Perhaps the most noteworthy aspect of the mass balance analyses is the less-than-complete exchange of Na^+ for K^+ . In general, owing to its ionic radius and other factors, K^+ tends to exhibit significantly higher sorption tendency than Na^+ . The fact that a portion of the K^+ arrived with the SCN^- at the discharge well may suggest incomplete rock/water interaction, although alternative retardation mechanisms cannot be ruled out. One observation in support of alternative retardation mechanisms is a slight decrease in SCN^- concentration with time observed

within the time-integrated groundwater samples collected during the testing. Selected samples, which were analyzed at their time of collection, were subsequently reanalyzed days later, whereupon a slight (1% to 2%) decrease in the SCN^- concentration was observed. Two explanations of this phenomenon are currently under consideration: (1) bacterial action, and (2) adsorption. The latter mechanism may be facilitated by means of colloidal suspensions residual from borehole drilling fluids.

Formation Characteristics

The discussions within the previous sections suggested that formational heterogeneities are present vertically across the McCoy Canyon flow top. In light of this information, it is reasonable to assume that heterogeneities might also be encountered over similar lateral distances.

Theoretically, a mirror-image symmetry should develop between the cones of impression and depression at the recharge and discharge wells under conditions of ideal homogeneity and isotropy within the flow top and equivalent well efficiencies and under conditions of equal flow. During the DC-7/8 tracer testing, a definite asymmetry developed wherein the cone of depression at DC-7 was on the order of 77 ft (23.5 m), while only a 2 ft (0.6 m) cone of impression developed at DC-8. Based on the analyses of hydraulic properties referred to earlier, the borehole skin effects associated with the testing interval were

determined to be negligible. This suggests that lateral heterogeneities may also be present in the vicinity of the two boreholes. For example, such asymmetry could result from a local pinch-out of a more highly transmissive horizon within the flow top.

Collectively, the observations regarding potential heterogeneities within the flow top support the previous discussions and implications regarding dispersion scale-dependency. Regional assessments of dispersion should be substantiated with tracer experiments at a representative scale.

Testing and Analytical Methodologies

To maximize the accuracy of results as well as the chances for success of any experiment, test conditions should provide the highest degree of fidelity achievable with regard to the assumptions and requirements of the analytical model proposed. In the experiments described above, it is seen that certain variances from ideal conditions are unavoidable, in particular, when working with preexisting facilities, resource constraints, as well as within very deep horizons. Nevertheless, it remains a responsibility of the investigators to evaluate the opportunities for improved accuracy that could arise from a better system or procedural design. Equally important, may be opportunities for modification and/or improvement of the analytical tools used to provide the parameter estimates.

For example, the results of the basalt tracer experiments show that, in testing deep formations by the tracer methods described above, estimates of longitudinal dispersivity may, to varying degrees depending on specific testing conditions, be affected by "lag time uncertainties" as well as borehole dispersion phenomena. As discussed earlier, the amount of time required for a tracer to cycle through the borehole and tubing strings before reaching its detection or sampling point is referred to as lag time. Lag time is, thus, a correction factor that affects both the estimates of dispersivity and effective porosity. The lag time is generally determined by means of the flow rate measurement applied to the displacement of the borehole/tubing volume storage. A dispersion sensitivity analysis was performed by using a range of lag time estimates for the SCN⁻ test. This evaluation revealed that the lag time correction is among the most sensitive factors of the analysis.

Borehole dispersion phenomena may also contribute to analytical errors by violating assumptions regarding instantaneous-pulse injection of the tracer into the formation. It is further assumed that the time concentration distribution of the tracer within the formation is representative of that which is observed at the discharge point. The result of failing to account for borehole dispersion would be overestimation of the magnitude of formation dispersivity. Such problems may be dealt

with in several ways, some of which require experimental design modifications and others that are analytical. Examples of the former methods might include downhole release of tracers, downhole tracer detection, and density compensation of tracer solutions. The last item, density compensation or gravity flow, remains a consideration in situations where mechanical mixing of the tracer would be difficult or impossible, such as through straddle packers which do not permit mechanical access to the test interval. A dense tracer solution released above the top packer could aid in rapid dissemination of the tracer through out the test horizon. Preliminary experimental simulations carried out at the University of Arizona have shown the potential for such mixing, but these same experiments suggest that the relationship between volume of tracer, solution density, rate and distance of dispersion, borehole volume, and rate of crossflow must be accounted for carefully. In actuality, such information may be as obscure as estimates of the targeted parameters.

The type-curve methodology developed by Gelhar (1982), when used in conjunction with the recirculating test configuration and single pulse input, has the advantage that the shape of the tracer breakthrough curve is very sensitive to dispersivity. This is in contrast to the more frequently used step input (Webster, et al., 1970; Grove and Beetem, 1971; Robson, 1974; Mercer and Gonzalez, 1981) in which dispersion affects only the

shape of the initial, low concentration portion of the curve. This method is believed to be most accurate for ϵ values less than 0.1. Transverse dispersion is ignored within this analysis on the basis that its effects are believed to be negligible within the $\epsilon < 0.1$ range. Some further development of the analytical methods has been carried out. This development has involved generation of convoluted type curves that account for such cases as (1) step input with constant tracer concentration, (2) exponentially decreasing tracer input corresponding to ideal mixing within the borehole, and (3) corresponding pulse input (self-convolution). The last case is expected to be useful in the analysis of the second breakthrough that occurs when the recirculating test has been run for a sufficient length of time. This phenomenon can be used as a basis for improving the estimates of lag time.

CONCLUSIONS

The above discussion provides typical examples of the design logistics, analytical limitations, and degree of interpretation commonly present in the performance of field tracer experiments. It further serves to examine the particular logistics associated with experimentation in deep formations as well as aspects of groundwater flow mechanics associated with flood basalts.

Assuming that the goal of such field characterization exercises is generally to provide a sufficient data base for

solute transport modeling of the groundwater flow system on a more regional scale, the issue of dispersion scale dependency remains a matter worthy of resolution for the medium under study. The approaches available for such an assessment include the following:

- Performance of experiments at scales approaching the scale of interest
- Performance of several experiments on varying scales as a means of defining the asymptotic value of macrodispersivity
- Use of recently developed stochastic methods of evaluation.

The method of approach chosen for any particular situation will naturally depend on subjective judgment in light of the constraints present.

In addition to the role of heterogeneity in controlling the dispersive characteristics of aquifers, a general understanding of the distribution of porosity is required, particularly if estimates of effective porosity are to be used for velocity calculations. The distribution of porosity seems, at present, to be a matter that is more easily understood for granular porous media than for basalt. Nevertheless, it is believed that with more testing at larger scales a working understanding can be reached.

Certain questions regarding the chemical dynamics associated with groundwater transport would be better resolved by a testing methodology that avoids the establishment of excessively high hydraulic gradients and, hence, high velocities (e.g., borehole dilution techniques); thereby allowing reaction times which are more typical of natural transport conditions. Thus, in addition to the estimation of hydromechanical dispersion, estimates of matrix diffusion, colloidal transport, and other transport factors could be made. This would serve to provide a more exact segregation of the individual components of the porosity model given in Equation 6.

The ion exchange data obtained from the KSCN experiment suggest that, through proper selection of tracers, estimates of retardation properties of the porous medium can be obtained. One method might involve "piggybacking" of sorptive and nonsorptive tracers during the same test. A retardation factor (RF) could, thus, be obtained by comparing the respective breakthrough curves of the tracers.

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TABLE 1. Major Constituent Hydrochemistry of Deep Basalt Groundwaters at the Hanford Site.

Major Constituents	Composite Grande Ronde Sample from DC-7/8	Average of Grande Ronde Samples
pH	9.8	9.6
Alk (HCO ₃ ⁻)	198	157
HCO ₃ ⁻	82	69
CO ₃ ⁼	42	95
Cl ⁻	127	221
F ⁻	37	27
SO ₄ ⁼	74	92
Na ⁺	235	269
K ⁺	3.1	9.7
Mg ⁺⁺	<0.01	0.04
SiO ₂	98	108

Note: All values are given in p/m except pH.

Table 2. Mass Balance Results for SCN^- and $\Sigma(\text{K}^+ + \text{Na}^+)$ from DC-7/8 KSCN Tracer Test.*

Species	Mass Injected, g (equivalent weights)	Mass Recovered, g (equivalent weights)	Percent Recovery
KSCN	350 (3.60)	NA	NA
SCN^-	209 (3.60)	125.5 (2.16)	60
K^+	140.7 (3.60)	15.2 (0.39)	11
Na^+	0 (0)	49.2 (2.14)	NA
$\Sigma(\text{K}^+ + \text{Na}^+)$	140.7 (3.60)	64.4 (2.53)	70

NOTE: Results show that mass balance between primary anions and cations involved is within 15%.

KSCN = potassium thiocyanate.
NA = not applicable.

*From Leonhart et al., 1982.

FIGURE 1. Location of the Columbia Plateau, Hanford Site, and Test Site.

FIGURE 2. Stratigraphic nomenclature, Columbia River Basalt Group/Ellensburg Formation, Pasco Basin (showing stratigraphic position of test horizon).

FIGURE 3. Borehole C-7/8--geologic and geophysical logs and location of test interval.

FIGURE 4. Schematic of dual borehole recirculating tracer test conducted on January 22 - 24, 1982.

FIGURE 5. Cross-sectional schematic of recirculating tracer test equipment configuration.

FIGURE 6. Time/concentration response of SCN^- , K^+ , and Ca^{2+} during tracer testing.

FIGURE 7. Type-curves for two-well pulse input test with equal flow (after Gelhar, 1982).

FIGURE 8. Type-curve match for SCN^- tracer data.

FIGURE 9. Scale - relationships for field estimates of longitudinal dispersivity (after Lallemand-Barres and Peaudecerf, 1979).

FIGURE 10. Static and dynamic fluid temperature logs across McCoy Canyon flow top.

FIGURE 11. Relationship of effective porosity, hydraulic conductivity, and effective test zone thickness.

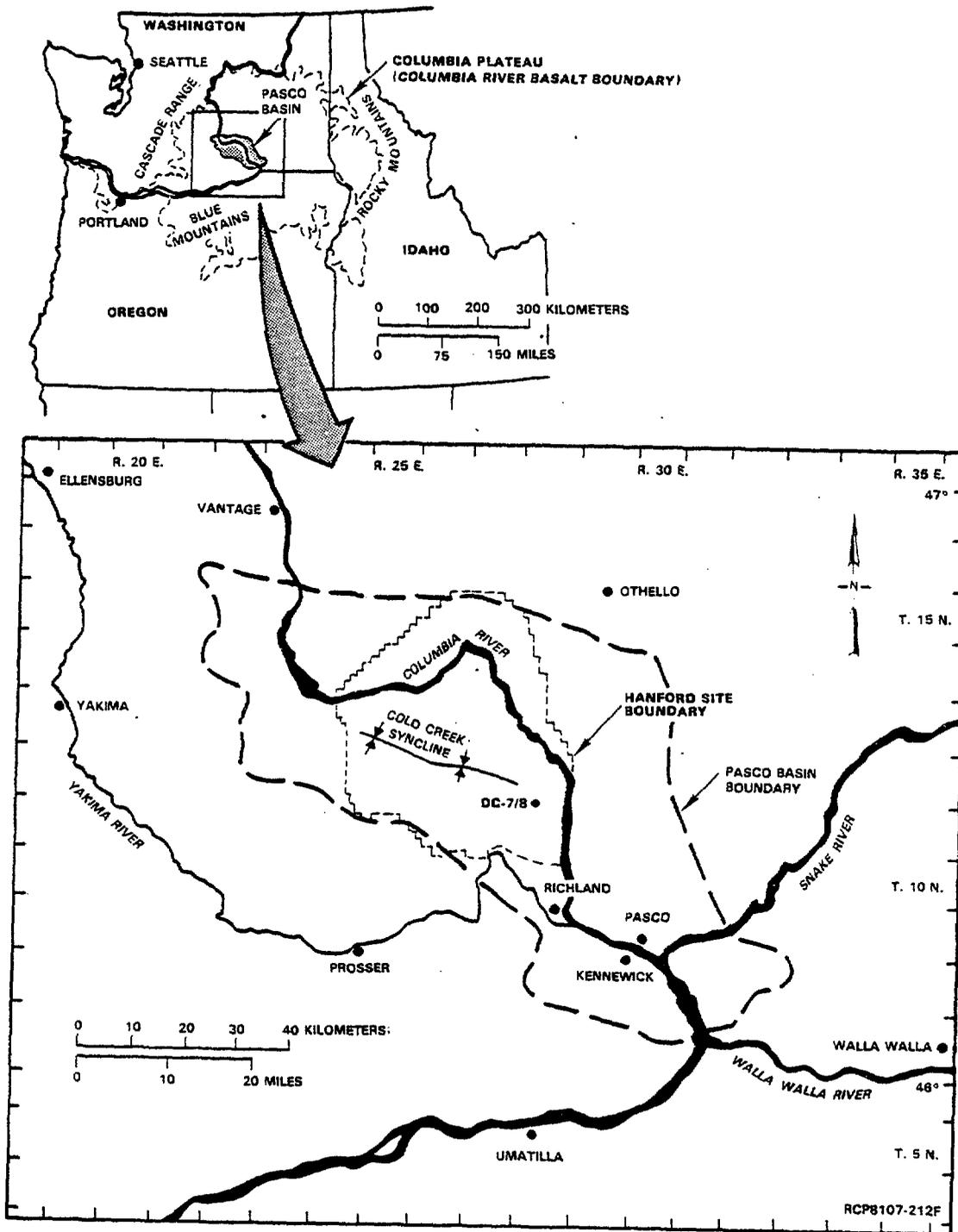


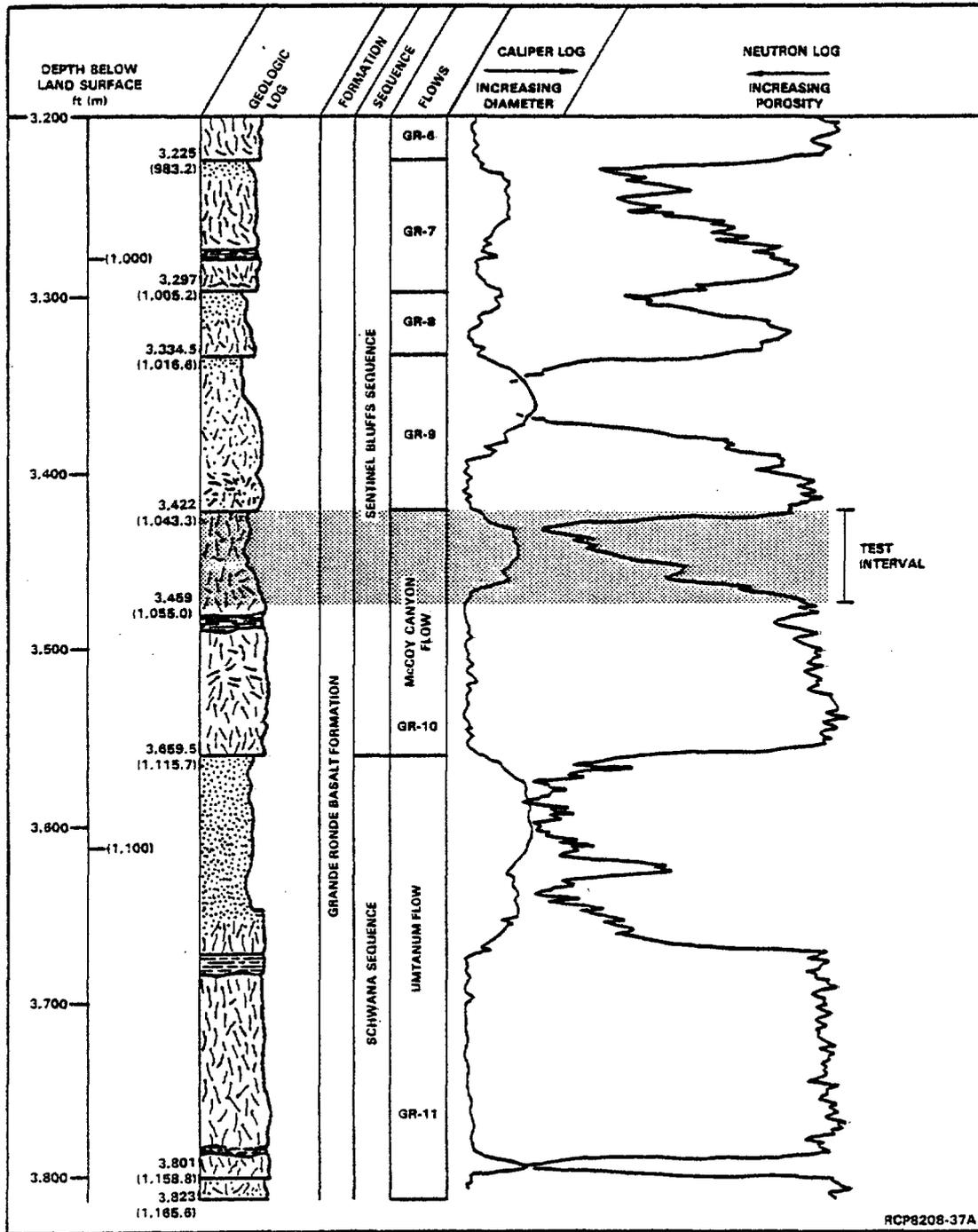
FIGURE 1

PERIOD		EPOCH	GROUP	SUBGROUP	FORMATION	MEMBER OR SEQUENCE	SEDIMENT STRATIGRAPHY OR BASALT FLOWS		
QUATERNARY	Pleistocene/Holocene								
QUATERNARY	Pleistocene/Holocene	Pleistocene			Hanford	SURFICIAL UNITS	LOESS SAND DUNES ALLUVIUM AND ALLUVIAL FANS LANDSLIDES TALUS COLLUVIUM		
	Pleistocene						Ringold	TOUCHET BEDS PASCO GRAVELS	PLIO-PLEISTOCENE UNIT UPPER RINGOLD MIDDLE RINGOLD LOWER RINGOLD BASAL RINGOLD
TERTIARY	Miocene		Columbia River Basalt Group	Yakima Basalt Subgroup	Saddle Mountains Basalt	ICE HARBOR MEMBER			GOOSE ISLAND FLOW MARTINDALE FLOW BASIN CITY FLOW LEVEY INTERBED
						ELEPHANT MOUNTAIN MEMBER	UPPER ELEPHANT MOUNTAIN FLOW LOWER ELEPHANT MOUNTAIN FLOW RATTLESNAKE RIDGE INTERBED		
						POMONA MEMBER	UPPER POMONA FLOW LOWER POMONA FLOW SELAH INTERBED		
						ESQUATZEL MEMBER	UPPER GABLE MOUNTAIN FLOW GABLE MOUNTAIN INTERBED LOWER GABLE MOUNTAIN FLOW		
						ASOTIN MEMBER	COLD CREEK INTERBED		
						WILBUR CREEK MEMBER	HUNTZINGER FLOW		
						UMATILLA MEMBER	WAHLUKE FLOW SILLUSI FLOW UMATILLA FLOW MABTON INTERBED		
						Wanapum Basalt	PRIEST RAPIDS MEMBER	LOLO FLOW ROSALIA FLOWS QUINCY INTERBED	
							ROZA MEMBER	UPPER ROZA FLOW LOWER ROZA FLOW SQUAW CREEK INTERBED	
							FRENCHMAN SPRINGS MEMBER	APHYRIC FLOWS PHYRIC FLOWS	
						Grande Ronde Basalt	SENTINEL BLUFFS SEQUENCE	VANTAGE INTERBED UNDIFFERENTIATED FLOWS ROCKY COULEE FLOW UNNAMED FLOW COHASSETT FLOW UNDIFFERENTIATED FLOWS MCCOY CANYON FLOW	
								SCHWANA SEQUENCE	INTERMEDIATE-Mg FLOW LOW-Mg FLOW ABOVE UMTANUM UMTANUM FLOW HIGH-Mg FLOWS BELOW UMTANUM VERY HIGH-Mg FLOW
						↓ AT LEAST 30 LOW-Mg FLOWS			

ELLENSBURG FORMATION

RCP8108-1H

FIGURE 2



RCP8208-37A

FIGURE 3

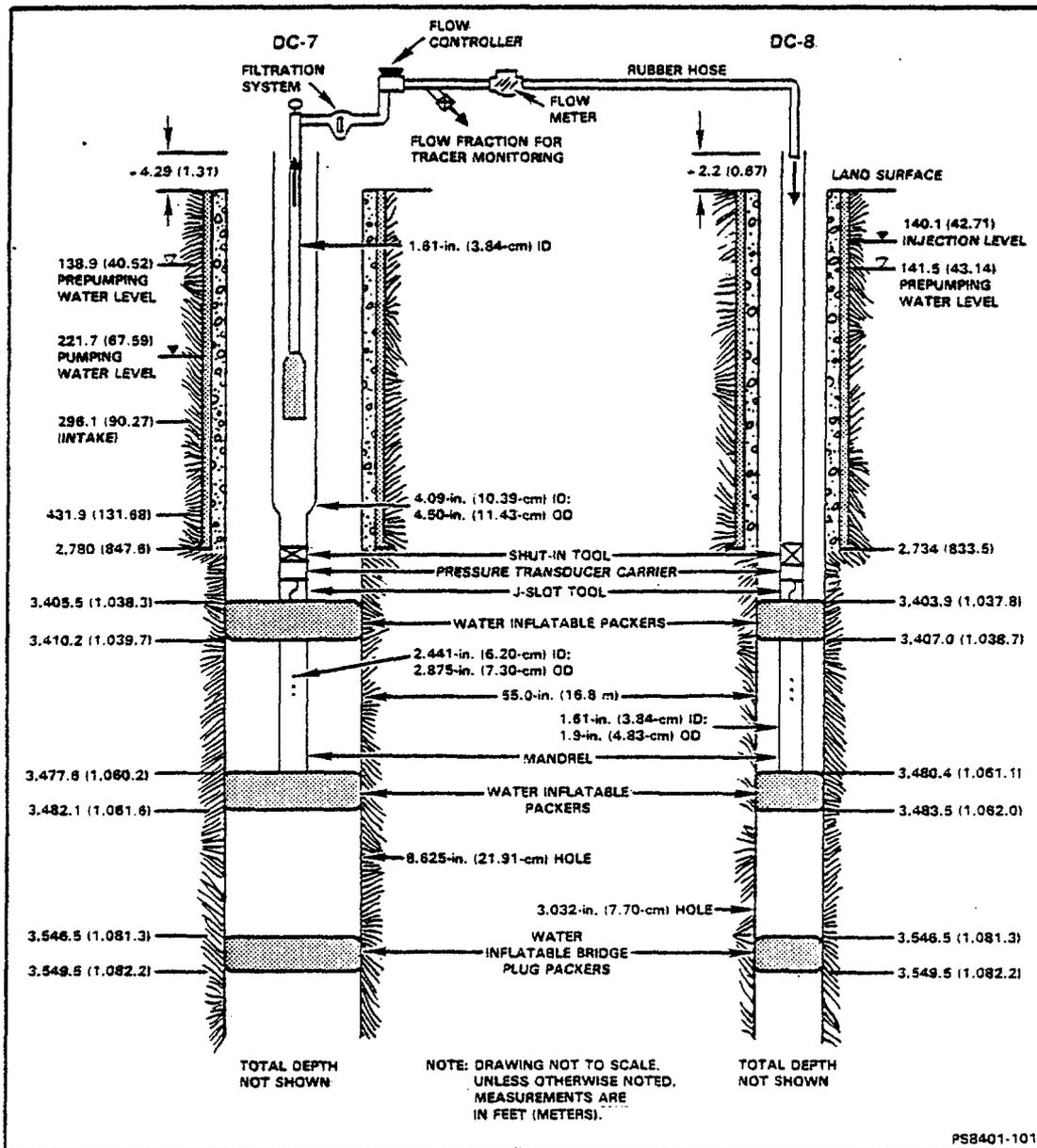
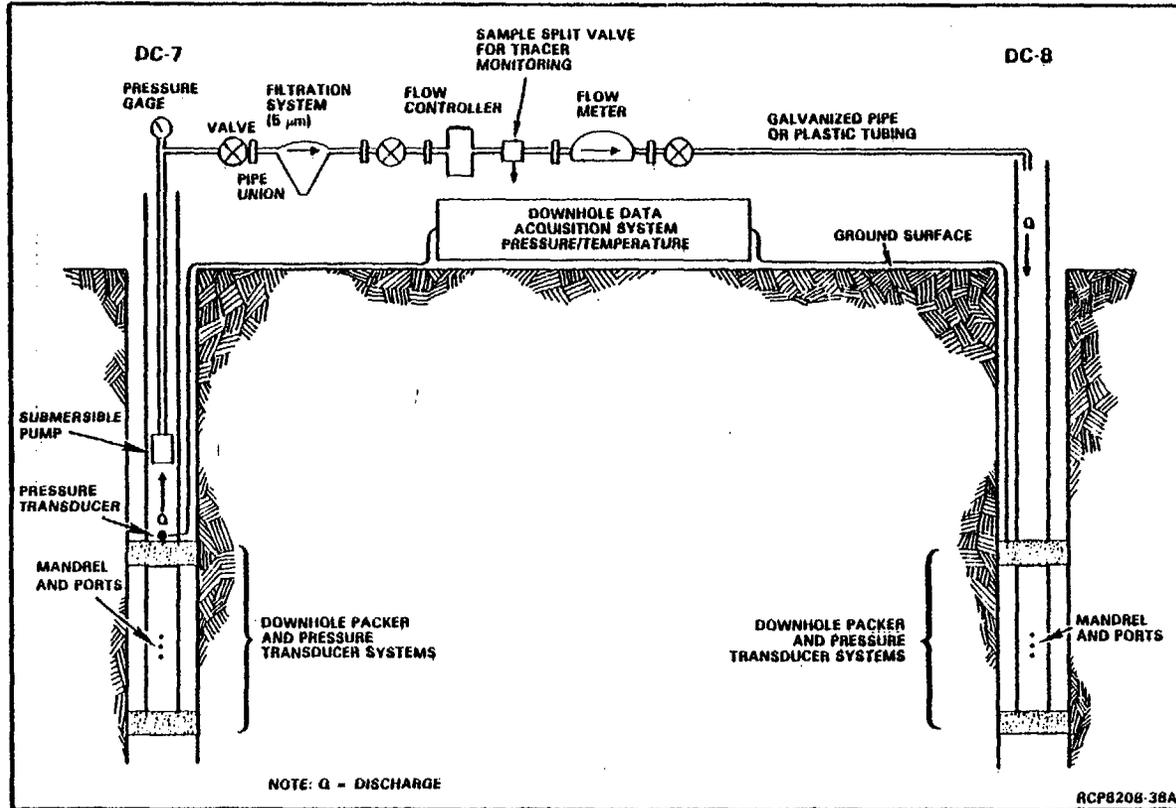


FIGURE 4

FIGURE 5



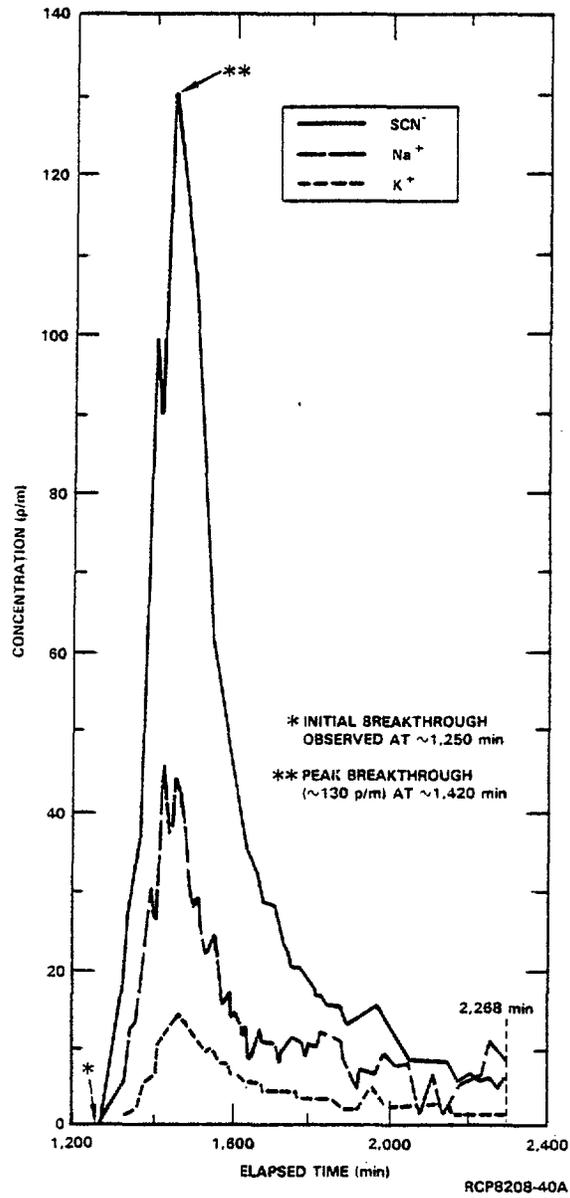


FIGURE 6

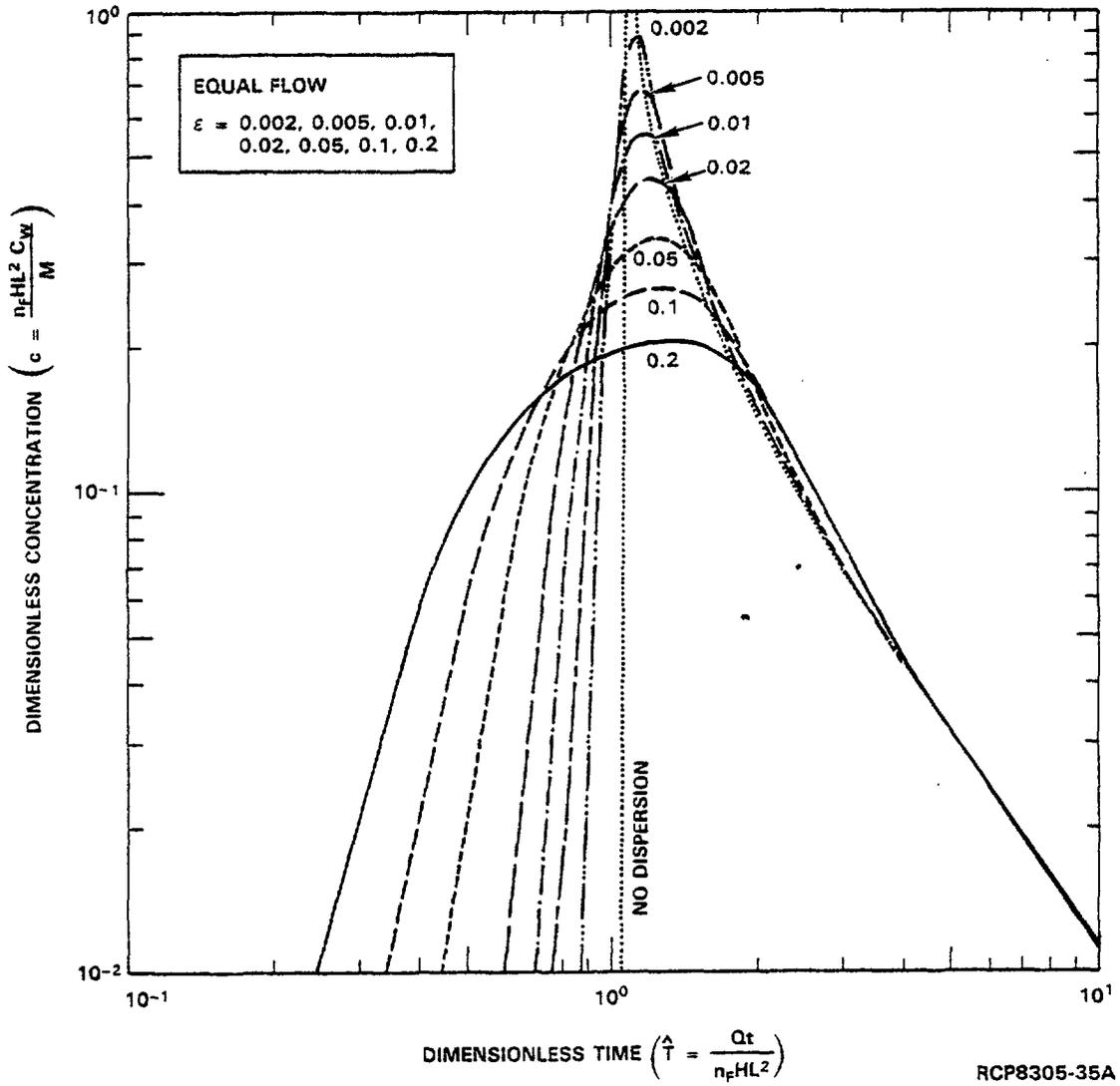


FIGURE 7

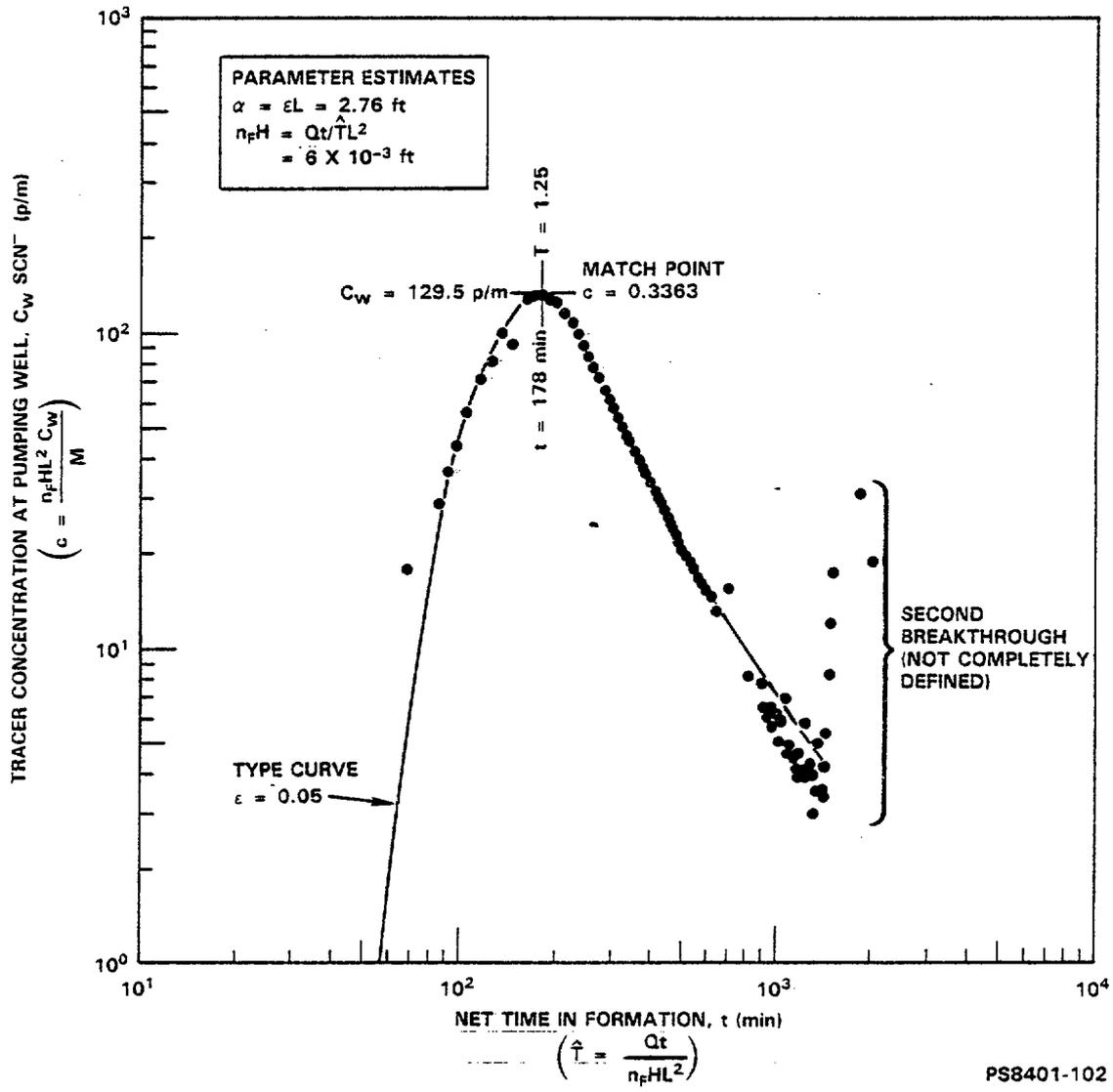
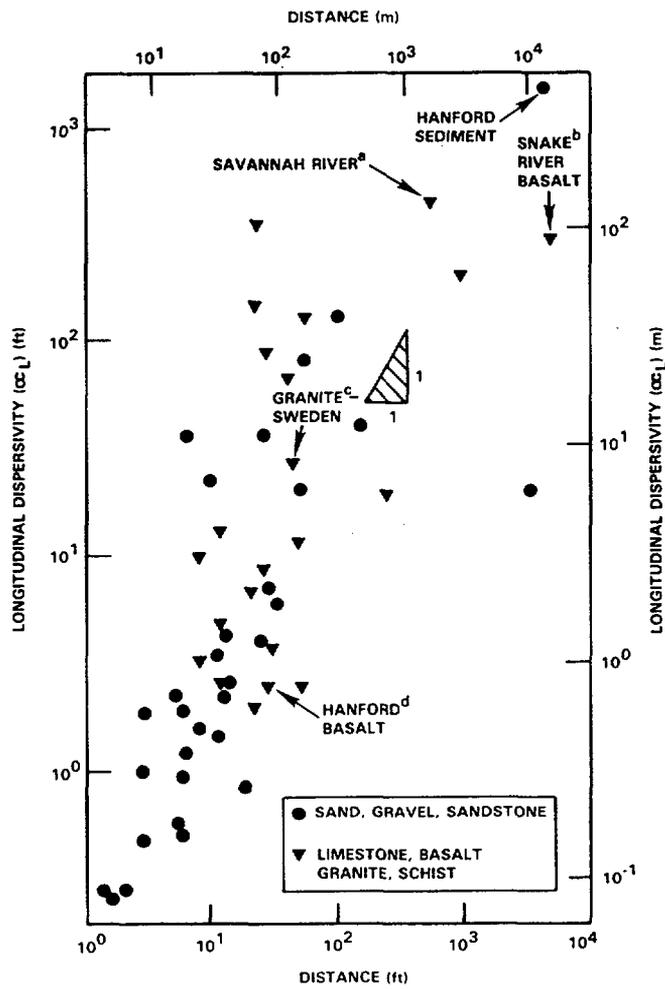


FIGURE 8



^aWEBSTER et al., 1970

^bROBERTSON, 1974

^cGUSTAFSSON AND KLOCKARS, 1981
LANDSTROM AND KLOCKARS, 1978

^dBAKR et al., 1980

LEONHART et al., 1982

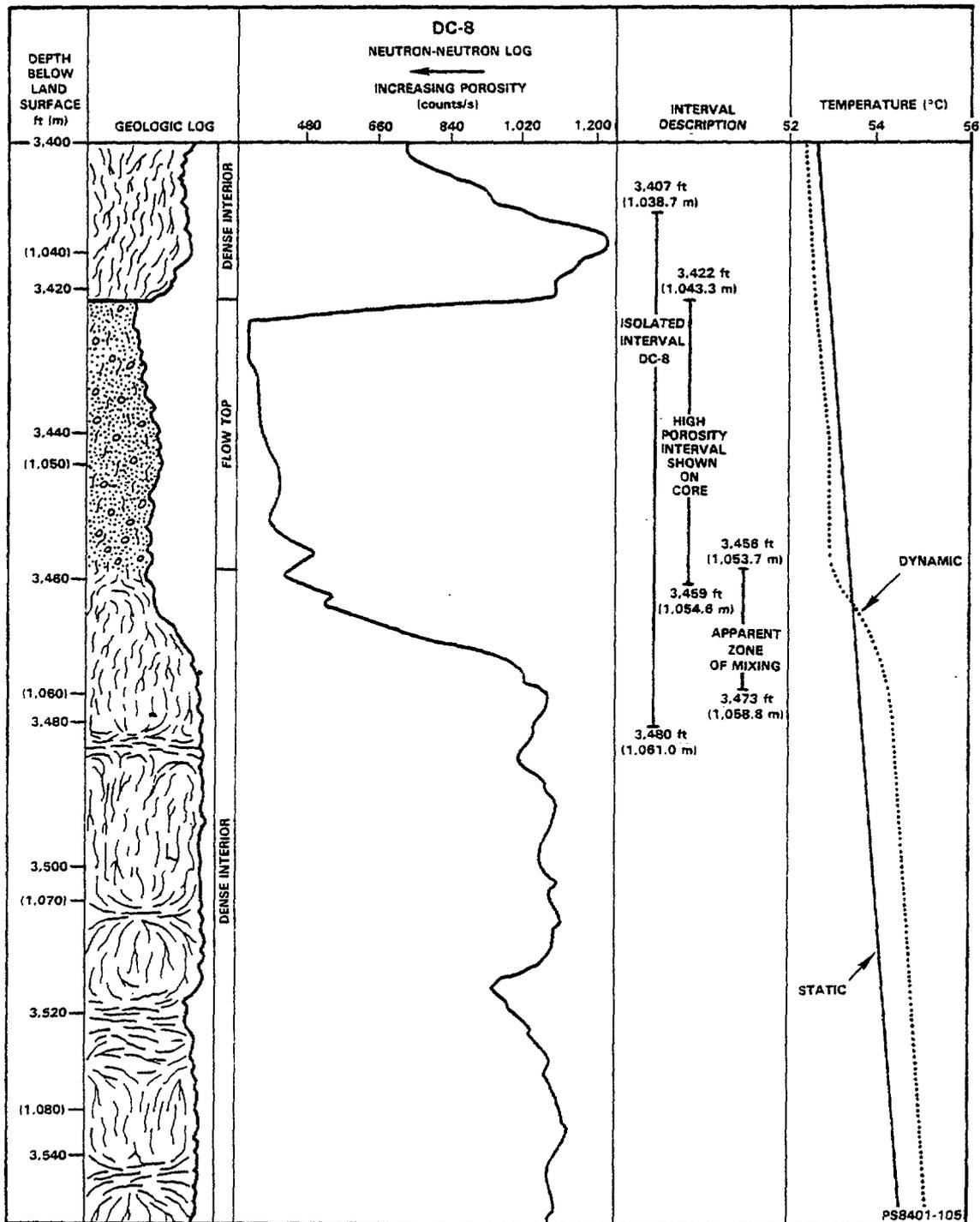
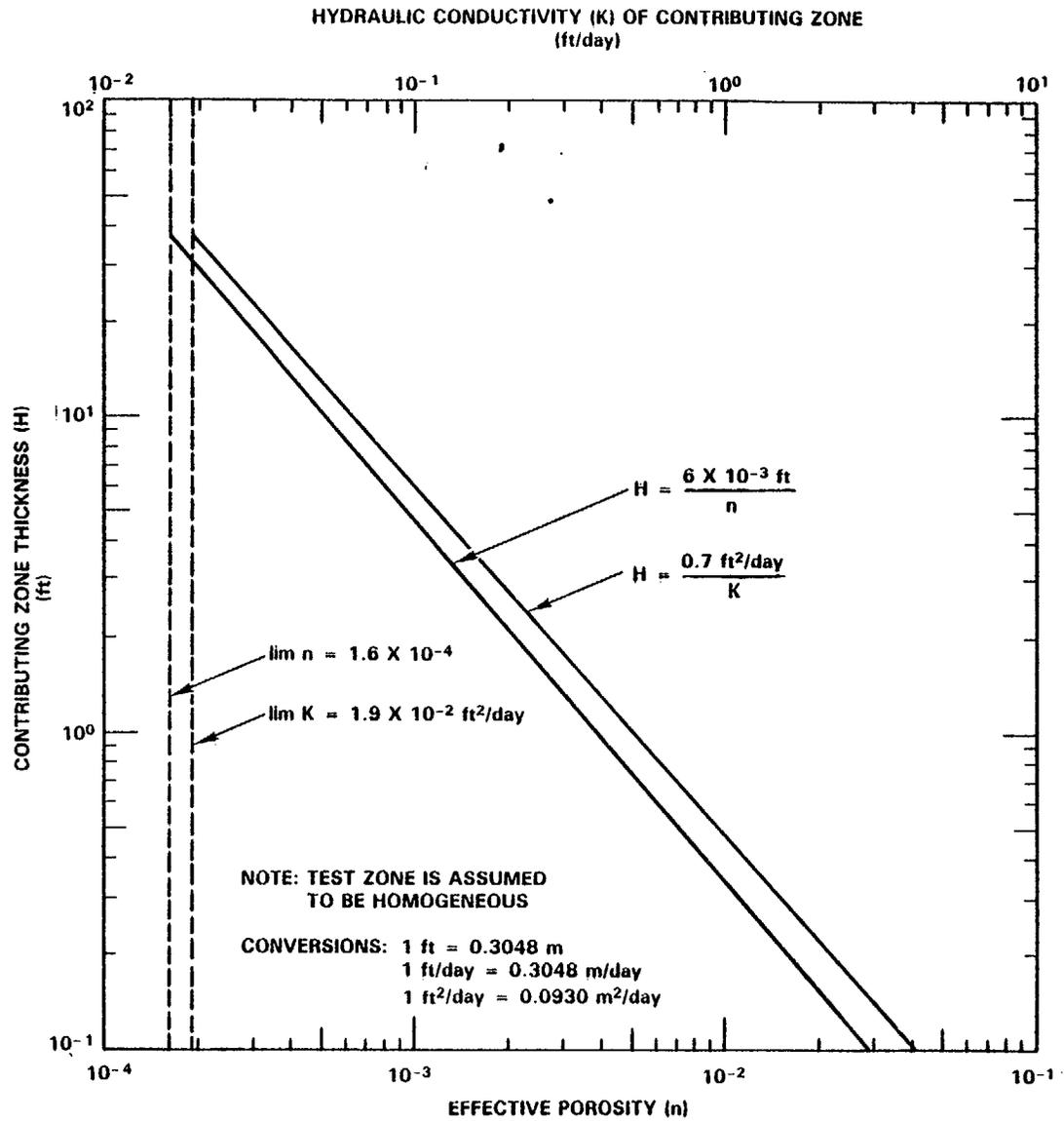


FIGURE 10

FIGURE 11



Enclosure C

Nuclear Regulatory Commission Letter Review

- A. May 29, 1984, Nuclear Regulatory Commission to Department of Energy-Richland Operations Office, "Hydrologic Test Data Review."

The Nuclear Regulatory Commission (NRC) review team visited the Basalt Waste Isolation Project (BWIP) in Richland, Washington during January 9-16, 1984. The purpose of the visit was to review issued and rough draft hydrologic interval reports, preliminary hydrologic data, and data collection procedures. This NRC review was the second of its type at BWIP; the first having been held in July 1982.

The following addresses the "General Comments" contained in the May 29, 1984 letter.

General Comment

- 1.0, Page 2, "Slug tests conducted by BWIP are considered to be adversely affected by wellbore conditions (e.g., wellbore friction, wellbore storage, skin effects)"

Response

Slug tests are a recognized standard hydrologic test method and have been used successfully in characterization studies for the past 30 years. Since the original slug test theory based on a line-source solution was first presented by Ferris and Knowles (1954), considerable progress and improvement in slug-test analysis has occurred. The historical development of slug-test analytical solutions is briefly discussed in a recent BWIP document by Thorne and Spane (1984).

Specific Comment Responses

- o Wellbore Friction: The BWIP is cognizant of the impact that test system friction can have on surface-based, water level and/or pressure measurements. The following two-fold approach was adopted by the BWIP to minimize the affect of friction (as well as other wellbore effects) in hydrologic test response:
 1. Acquisition of Downhole Pressure Probe Systems. The installation of pressure sensors at test formation depth, eliminates the effect of friction on downhole hydrologic responses recorded during testing. Efforts were initiated as early as 1978 by the BWIP to acquire through leasing (e.g., Lynes, Inc.) or purchase (e.g., TAM, Inc. and Seling Corp.) appropriate downhole pressure probe systems. Although not all test intervals have been

instrumented with downhole equipment in the past, acquisition of the TAM/Seling test system has allowed instrumentation of most zones over the past two years. This was recognized by the NRC in the May 29, 1984 letter (page 3), "...The NRC staff notes the following significant improvements in BWIP hydrologic test procedures:...trend toward the use of downhole pressure monitoring and shut-in equipment...."

2. Friction Analysis. The Darcy-Weisbach equation and Reynolds number relationships are used to assess the importance of friction on surface-based, water-level measurements recorded during slug testing. Because of the greater fluid velocities involved, under-damped slug-tests (i.e., damped oscillatory response) tend to be influenced to a greater degree by test system friction than over-damped slug tests (exponentially decayed response). To minimize test system friction effects on under-damped, slug-test analysis, only late-time data (i.e., data after the first complete oscillatory cycle), with established laminar flow conditions, are subject to analysis. Recent correspondence from Dr. Garth Van der Kamp (Saskatchewan Research Council) also indicates that the approximate solution originally described in Van der Kamp (1976) may be modified to account for the effects of friction. Results of this friction study will be incorporated in a final BWIP report by early calendar year 1985, which will address the applicability of the "Van der Kamp" method for under-damped slug-test analysis under Hanford Site test conditions.

Other Specific Comment Responses

- o Wellbore Storage. Wellbore storage is accounted for in both the over-damped (Cooper, et al., 1967) and under-damped (Van der Kamp, 1976) slug-test solution.
- o Skin Effects. The traditional hydrologic approach for over-damped and under-damped slug-test analysis assumes no skin effects (i.e., $s = 0$). Ramey, et al. (1975) were able to show that skin effects can cause a discernable shift in over-damped, slug-test response time. These studies, however, also showed that transmissivity estimates obtained by the method described by Cooper, et al. (1967), i.e., $s = 0$, are accurate and not sensitive to skin effects.

General Comment

2.0, Page 2, "Point measurements in single, small-diameter boreholes are considered to be of questionable value in characterizing large volumes of rock"

Response

Point measurements of hydraulic head, hydraulic properties (e.g., transmissivity, hydraulic conductivity, etc.) and groundwater chemistry obtained from widely-spaced single boreholes are requisite for the understanding of areal hydrologic relationship(s) for the various basalt groundwater systems. Measurements obtained from multiple borehole sites provide additional insight pertaining to aquifer-system response to an induced stress (e.g., large-scale interference test) within localized areas. Multiple borehole tests also provide the best opportunity to estimate selected hydrologic parameters; such as storativity, effective porosity, and dispersivity and for assuming the degree of heterogeneity and anisotropy within an aquifer system. Characterization studies, which integrate information obtained from areally located single borehole and multiple borehole sites, are best suited for addressing far- and near-field hydrologic relationships. Large-scale hydraulic stress tests to be conducted will utilize large diameter pumping wells to maximize stress.

General Comment

3.0, Page 2, "Measurements of vertical permeability, long-term head, and effective porosity are needed"

Response

The BWIP recognizes the importance of acquiring in-situ determinations of the above-mentioned parameters for performance assessment and groundwater travel-time estimates. The following pertain to each of the identified parameters:

- o Vertical Permeability: The BWIP has examined available test methods for evaluating vertical permeability of basalt flow interiors (see Javandel, 1983). In addition, one of the identified acceptable methods (i.e., the "ratio method") was field evaluated at multiple-borehole site DC-4/5 in 1983. An evaluation of the applicability of this test method to characterize vertical permeability of basalt flow interiors, utilizing straddle-packer test equipment is contained in Spane, et al. (1983). The focus of future test evaluations of vertical permeability methods for multiple and single-borehole sites is also discussed briefly in the report. Plans for obtaining vertical permeability estimates for selected basalt flow interiors in the reference repository location (RRL) will be included in the forthcoming strategy document for large-scale hydrologic testing (RRL-2B) and the Site Characterization Plan.
- o Long-Term Head: The time-variant response of hydraulic head can provide information concerning aquifer-system response to natural processes (e.g., recharge/discharge relationships) and man-related activities (e.g., groundwater withdrawal). Prior to 1983, the BWIP depended primarily on existing boreholes to assess time-variant response within selected aquifers at the Hanford Site. These existing boreholes normally monitor a single hydrogeologic unit within the Saddle Mountains and Upper Wanapum basalt.

To provide information concerning the time-variant response of eight selected hydrogeologic units within the Columbia River Basalt Group and the unconfined aquifer in the RRL, three piezometer test sites were constructed (i.e., DC-19, DC-20, and DC-22). Details concerning piezometer construction are contained in Jackson, et al. (1984). Hydrologic measurements at the piezometer sites were initiated in April 1984. Water-level and downhole formation pressure measurements for each monitored zone are contained in monthly reports issued by the Drilling and Testing Group (e.g., Bryce and Yeatman, 1984).

Information obtained from the piezometer sites, as well as at the other boreholes within the Hanford Site monitoring network will be integrated into conceptual and numerical models to improve the delineation of groundwater flow patterns and travel-time estimates within various hydrogeologic units.

- o Effective Porosity: Currently, estimates of effective porosity for basalts are limited to five hundred laboratory core analyses and two in-situ field tests. The BWIP recognizes the need for additional in-situ determinations of this parameter. Plans for obtaining estimates of effective porosity (i.e., from field tracer tests) for selected basalt horizons in the RRL are discussed in the strategy document for large-scale hydrologic testing - RRL-2B (in preparation) and the Site Characterization Plan (in preparation).

General Comment

4.0, Page 2 "The occurrence of non-standard test responses, such as the 'overshoot' phenomenon, has not been adequately evaluated by BWIP."

Response

The "overshoot" phenomenon identified by the NRC in Comment 4.0 has been recognized by the BWIP as a wellbore effect, which influences surface-based, water-level and pressure measurements. Hanford Site test intervals which display this effect are more prevalent in zones generally possessing: a high transmissivity, undissolved gas in the borehole fluid column, a small fluid-column diameter (i.e., approximately <1.75 in.), and long fluid-column length (i.e., approximately >800 ft). Several factors have been identified previously by the BWIP and others as responsible for this type of well-bore effect. Recognized factors included: multi-phase borehole conditions, fluid column temperature disequilibrium, and fluid column inertial (momentum) effects. All three factors have been identified as operative under certain Hanford Site test conditions, and will be the object of BWIP staff and consultant studies during fiscal year 1985. In addition, a field evaluation of this phenomena is planned for a high transmissivity test zone at borehole DB-2. The field evaluation will include surface-based and downhole pressure instrumentation, as well as static and dynamic fluid-temperature surveys. A test specification, which details the design and performance of the field evaluation at borehole DB-2, will be issued in early calendar year 1985.

It should be noted that surface-based measurements displaying this type of behavior are analyzed or included in hydraulic property characterization. As noted previously in the response to General Comment 1.0, the use of downhole pressure sensors eliminates the effects of this, as well as other, wellbore effects; and therefore, is preferred by the BWIP in performing transient testing.

The following addresses NRC Conclusions and Recommendations.

Conclusions and Recommendations

1.0, Pages 2 & 3, "As stated...in this letter..., NRC concludes that much of the single-well data collected to date is questionable in terms of its numerical accuracy. Nevertheless, the data collected has been used by BWIP in the past as the basis for preliminary performance assessments and candidate horizon selection (cf., BWIP Site Characterization Report (1982), Repository Horizon Identification Report (ST-28, 1983)). NRC considers use of the existing data in this manner to be inappropriate. Repository performance assessments and program decisions based on the present data base should be carefully qualified by BWIP with regard to reliability. We consider that an appropriate use of the existing data base lies in qualitative planning for future tests...."

Response

The BWIP believes that values obtained from previous single-well tests are defensible and representative of conditions for the various test intervals in the vicinity of the borehole site. When used collectively, areal information obtained from single-well tests can provide insight as to variability and heterogeneity of various hydrologic properties of aquifer systems within a region. The BWIP believes that information obtained from single-well tests is appropriate, not only in the "qualitative planning for future tests," but in the manner presented previously in the BWIP Site Characterization Report (1982) and Repository Horizon Identification Report (ST-28, 1983). This is consistent with other NWTS hydrologic investigations that depend on both single and multiple-borehole derived data, currently being conducted at other regional sites in the United States.

The value of single-well derived measurements and its association with data obtained at multiple-well sites was also discussed previously in the response to General Comment 2.0.

Conclusion and Recommendation

- 2.0, Page 3, "The NRC staff notes the following significant improvements in BWIP hydrologic test procedures:
- 2.a reverse circulation air drilling rather than drilling with mud in construction of the boreholes;
 - 2.b trend toward the use of down-hole pressure monitoring and shut-in equipment;
 - 2.c adoption of large-scale multi-well pump tests (as suggested in NRC STP 1.1)."

Response

- 2.a As a point of discussion it should be noted that the use of reverse circulation air-drilling does not eliminate invasion of "foreign" drilling fluid (i.e, air, detergent, overlying formation fluids) into individual zones during drilling.

As part of a continuing BWIP field assessment to examine the effects of drilling fluid invasion on hydraulic characterization of low permeability basalt horizons, the BWIP compared results of a series of tests conducted prior to and following administering drilling fluid across a basalt flow interior at borehole DB-2. The results of this study, which indicated no discernible impacts of drilling fluid invasion on hydraulic characterization of the flow interior tested, are reported in Spane and Thorne (1984).

The BWIP is planning to expand the field assessment of drilling fluid invasion to basalt zones of high permeability. A high transmissivity zone in the Wanapum, which was previously drilled with only water, has been identified as a candidate for testing during fiscal year 1985. A test specification which discusses the design and performance of this field evaluation will be available in early calendar year 1985.

- 2.b See response to General Comment 1.0 for discussion of the use and acquisition history of downhole pressure probe systems by the BWIP in support of Hanford Site field studies.
- 2.c See response to General Comment 2.0 concerning use and relationship of single- and multiple-well derived measurements.

Conclusion and Recommendation

3.0, Page 3, "For relatively deep hydrologic testing, such as that performed in the Grande Ronde formation at the Hanford site, NRC suggests that DOE consider the placement of pressure measurement devices at or near the test interval level. Although...NRC recognizes that there are potential difficulties with the utilization of downhole transducers, we consider that the use of downhole pressure transducers would eliminate or reduce the severity of numerous problems encountered during testing thus far, such as the effects of dissolved gases, temperature variations, wellbore friction, and wellbore compressibility on inferred pressures at depth."

Response

The BWIP is cognizant of the factors (i.e., wellbore effects) which can influence measurements obtained during transient testing. Efforts were initiated as early as 1978 by the BWIP to acquire through leasing and/or purchase appropriate downhole pressure probe systems to be used in support of the field testing program. It should be noted, however, that although wellbore effects can influence surface-based measurements during transient testing (i.e., under certain test conditions), it does not necessarily preclude their use for analysis. For additional discussion on specific wellbore effects refer to responses provided for General Comment 1.0 and 4.0.

Conclusion and Recommendation

4.0, Page 4, "NRC considers that a detailed field and office manual for hydrologic test design, procedures, analyses, and documentation should be produced by BWIP. The Basalt Operation Procedures Manual (RHO-BWI-MA-4) is currently deficient in these four aspects of hydrologic data reliability assurance and control. The improved procedures manual should contain sufficient information for BWIP hydrologists to avoid irregularities in these four aspects of geohydrologic site characterization..."

Response

Hydrologic tests used by the BWIP in characterization studies are standard "start-of-the-art" methods, which are accepted by the scientific community. RHO-BWI-MA-4 provides general guidelines for the design, performance, and analysis of hydrologic tests used by the BWIP. These general guidelines reference existing U.S. Geological Survey and Corp of Engineers general procedures for performance and analysis of specific hydrologic tests.

For specialized tests to be conducted by the BWIP (e.g., large-scale interference tests - RRL), detailed test specification and procedure documents will be prepared, which contain the design, test procedure, analytical method, and type of documentation to be utilized. These test specifications and procedures will serve as the general guide for the supervising test hydrologist(s) to conduct, analyze and document the specific test results.

Conclusion and Recommendation

5.0, Pages 4 & 5, "NRC recommends that future BWIP interval reports include the following information, in addition to the hydrologic and geologic information provided as standard material in the previously published interval reports:

- 5.1 Topographic/cartographic data for all borehole tops, including latitude, longitude, and elevation for all reference points;
- 5.2 Elevations of tops of major stratigraphic units penetrated by borehole;
- 5.3 Borehole deviation information based on gyroscopic survey data for paired or clustered boreholes used in multi-well tests;
- 5.4 Information pertaining to calibration of pressure transducers and other measuring devices;
- 5.5 All hydrologic test data collected for the given interval whether or not it is used in the report, including data from incompletd tests. Also, inferred storativity values should be presented."

Response

5.1, 5.2, and 5.3. Agreed. Items identified, which are not currently contained in BWIP interval reports, will be added in future revised issues.

5.4. All serial numbers of equipment used during testing will be identified in future reports. Calibration data availability will be referenced and not included in the report. Calibration information for test equipment, e.g., pressure transducers are kept on file with the Data Management Unit of the Systems Integration and Performance Assessment Department, BWIP.

5.5. Disagree. The intent of the internal support document is to discuss and present all tests which were performed and analyzed in the course of characterization. Tests which were aborted or unsuccessful (e.g., equipment failure, packer leakage, etc.) are identified and discussed in the report. Data for aborted tests are not included in the interval reports by the BWIP, unless analysis of results are attempted. The availability of this data, however, is referenced in the reports and can be obtained upon request from the Data Management Unit of the Systems Integration and Performance Assessment Department, BWIP.

With respect to "inferred storativity values," all recent BWIP documents report inferred estimates of storativity when reasonable values are obtained. As noted previously by Cooper, et al. (1967), Papadopoulos, et al. (1973), and in BWIP interval reports, estimates of storativity derived from slug-test analysis are highly qualitative and should be used with caution.

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