See D1021 7/21/86
To: J. Pohle
Communication No. 18

Mini-Report #1

ANALYSIS OF FLOW INTERIOR HETEROGENEITY: GROUND WATER TRAVEL TIME

Basalt Waste Isolation Project
Subtask 2.5
Numerical Evaluation of Conceptual Models

Prepared by

Terra Therma Inc.

for

Nuclear Waste Consultants

June, 1986

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June 30, 1986

Nuclear Waste Consultants
ATTN: Mark Logsdon
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Re: Subtask 2.5, Numerical Evaluation of Conceptual Models

Dear Mark:

With this letter, Terra Therma, Inc. submits the 2.5 Subtask status report for the Numerical Evaluation of Conceptual Models.

As a result of discussions with the BWIP team and the Project Technical Director, Adrian Brown, a list of questions were developed for the proposed conceptual models. The questions were used as a basis for specific analyses which were first attempted by relatively straight forward analytical procedures. Depending upon the results of these analyses, the questions were either answered satisfactorily or will require a higher level of analysis, such as numerical modeling.

The following mini-reports are attached for your review:

1. Analysis of Flow Interior Heterogeneity: Ground Water Travel Time

2. Analysis of Flow Interior Heterogeneity: Cumulative Flux

3. Evaluation of Residual Thermal Effects

3. Relationship of Hydrodynamic Dispersion to Compliance with Overall EPA Release Standards

4. Analysis of Drilling Response at the Hanford Site

A fifth question has been under study (Effect of Hydrologic Boundaries), but is not available for publication at this time.

The various mini-reports provide a status report of work in progress. The results to date have been interesting, and in some cases unexpected. The information and analyses provided in the mini-reports are the basis for on-going analyses which will be reported to NWC as they become available. Also, additional questions (mini-reports) will be started as these are completed.

The 2.5 Subtask mini-reports mark a transition into full Quality Assurance review and reporting. As you know a QA workplan has been developed for this subtask and implementation has begun.

If we can provide any additional information or clarifications, please do not hesitate to call me.

Sincerely,
TERRA THERMA, INC.

Fred Marinell for M. Galloway

Michael Galloway
BWIP Team Leader

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1.0 INTRODUCTION

1.1 GENERAL STATEMENT OF THE PROBLEM

The purpose of this analysis is to address the following question:

> Given a knowledge of bulk vertical hydraulic conductivity of a flow interior, to what extent is it important that we know how vertical permeability is distributed within the flow interior for the purpose of evaluating ground water travel time?

The BWIP Large-Scale Hydraulic Stress (LHS) Testing Program is designed in part to measure integrated (bulk) values of vertical hydraulic conductivity of basalt flow interiors. However, geologic evidence suggests that flow interiors potentially contain heterogeneous features, which could result in significant variations in hydraulic conductivity from one location to another (Gephart et al, 1983). Assuming that the bulk conductivity of a flow interior has been measured, it may be important for the NRC to know how useful this value is in evaluating ground water travel time.

1.2 RELEVANCE TO NRC

Subpart E of 10 CFR Part 60 requires that an evaluation be made of minimum pre-emplacement ground water travel time from the disturbed zone to the accessible environment (10 CFR 60.113(a)(2)).

The pre-emplacement ground water travel time (GWTT) requirement addresses ground water flow from the edge of the disturbed zone to the accessible environment along paths of likely radionuclide transport. Since interstitial ground water velocity is directly proportional to hydraulic conductivity, GWTT may be significantly affected by formation heterogeneity.

1.3 RELATIONSHIP TO OTHER SITE CHARACTERIZATION/REGULATORY TASKS

NRC and DOE performance modeling of the BWIP site has generally treated flow interiors as homogeneous equivalent porous media which can be characterized by bulk hydraulic properties. While this approach may be reasonable for simulating the hydraulic (head) response of the system, a significant question related to performance modeling is whether or not the assumption of homogeneity will correctly predict minimum ground water travel time.

To date, relatively little information exists on the hydraulic conductivity and effective porosity properties of dense basalt within flow interiors. In situ testing has consisted of a limited number of single borehole tests. While the majority of these tests have indicated extremely low hydraulic conductivity, two of the tests measured substantially higher conductivities. This could be interpreted to mean that while the majority of dense basalt has very low hydraulic conductivity, isolated intraflow structures with much higher conductivity could potentially exist. If isolated high permeability "windows" exist within flow interiors, the minimum travel time could be dominated by the properties of these anomalous structures.

There are currently no credible measurements of the bulk vertical hydraulic conductivity of flow interiors. Since the BWIP LHS program is designed in large part to measure this parameter, it is presumed that reliable bulk values of conductivity will be available in the near future.

2.0 OBJECTIVE

The objective of this analysis is to determine the relative sensitivity of GWTT to the heterogeneity of basalt flow interiors.

3.0 EVALUATION

3.1 OPERATIONAL APPROACH

The general approach to evaluating the sensitivity of GWTT to basalt flow interior heterogeneity is to consider the degree to which heterogeneity affects travel time within a single flow interior. If these errors are large relative to other uncertainties involved in performance assessment, more detailed analyses of flow interior heterogeneity may be warranted. If, however, the relative errors are small, then it may be concluded that flow interior heterogeneity need not be considered by the NRC in evaluating associated regulatory criteria.

3.2 CONCEPTUAL MODEL

3.2.1 Framework

Basalt flow interiors are considered to control vertical flow (leakage) between adjacent interflows. Flow interiors are generally characterized by colonnade and entablature jointing with a preferred vertical orientation. However, a variety of internal structures, generally related to the pattern and density of fracturing, have been observed within boreholes and outcrops. These structures include fanning entablature, shatter breccia, spiracles, and flow top/interior thickness irregularities. Such structures may potentially result in heterogeneity with regard to hydraulic/transport properties.

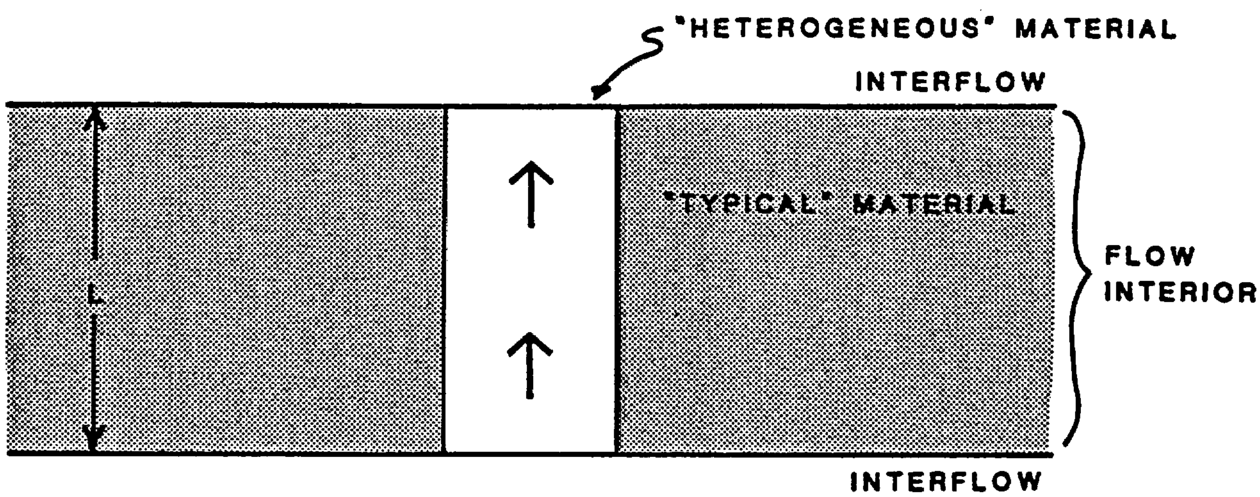
For the purposes of this study, a flow interior is conceptualized as being composed of "typical" material with low hydraulic conductivity and "heterogeneous" material with significantly higher conductivity (Figure 1). It is further assumed that the heterogeneous material extends completely through the flow interior (i.e., provides direct hydraulic communication between adjacent interflows).

3.2.2 Flow System

The ground water flow system within the interior is assumed to be characterized by one-dimensional (vertical) steady-state flow. The upper and lower boundaries of the flow interior are assumed to be maintained at constant (but different) hydraulic heads, resulting in a linear hydraulic gradient within the interior. Ground water velocities are in general, expected to be different depending on the material being considered. Bulk vertical hydraulic conductivity of the flow interior is considered to be a weighted average (by cross-sectional area) of the two material types.

In evaluating GWTT, each material type within the flow interior is treated as an equivalent porous medium with conditions appropriate for application of Darcy's law. GWTT is based on the (vertical) interstitial velocity of ground water flowing within the flow interior.

FIGURE 1. GEOMETRIC MODEL OF FLOW INTERIOR HETEROGENEITY
(VERTICAL SECTION)



EXPLANATION

↑ GROUNDWATER FLOW DIRECTION

3.3 TECHNICAL APPROACH

3.3.1 Formal Statement of the Problem

Given a geometric model of flow interior heterogeneity and the hydraulic conductivity contrast between typical and heterogeneous material, it is proposed that calculations be performed to compare GWTT based on (1) the actual formation characteristics (incorporating the heterogeneity) and (2) on bulk vertical hydraulic conductivity. Since the purpose of this analysis is to compare the two physical models, absolute travel times and fluxes need not be calculated. Instead relative values based on dimensionless quantities are compared.

3.3.2 Solution Techniques

GWTT is determined, based on interstitial fluid velocity calculated from the following form of Darcy's law:

(1) $$V = K\, i / n$$

where: V = average interstitial velocity

K = (vertical) hydraulic conductivity

i = hydraulic gradient

n = effective porosity

Clearly, the time taken for water to cross a thickness L of this material is given by:

(2) $$t = L / V = L n / (K i)$$

where: L = thickness of the flow interior

As it is assumed that the hydraulic gradient and thickness are the same for all pathways through the flow interior, it is clear that minimum GWTT time through the flow interior occurs within the material having the highest value of hydraulic conductivity divided by effective porosity.

3.3.3 Assumptions

Principal assumptions associated with analyses in this study are as follows:

1. Fractured rock is treated mathematically as an equivalent porous medium.
2. Ground water flow is linear and satisfies conditions required for application of Darcy's law.
3. Ground water flow within the flow interior is one-dimensional (vertical) and steady-state. Lateral flow does not occur between the two material types.

4. The top and bottom of the flow interior are maintained at constant (but different) hydraulic heads. The hydraulic gradient within the flow interior is linear.

5. Hydraulic conductivity and effective porosity are the only parameters which vary spatially within the flow interior. Hydraulic gradient and flow interior thickness are treated as constants.

6. Heterogeneous material extends completely across the flow interior.

7. Bulk vertical hydraulic conductivity is considered to be a weighted average (by planimetric cross-sectional area) of the conductivity of the two material types.

4.0 ANALYSIS

Analyses presented herein are based on the assumption that the flow interior is composed of "typical" material (of relatively low hydraulic conductivity) and "heterogeneous" material (of higher conductivity). The heterogeneous material is assumed to fully penetrate the flow interior.

4.1 BASIC RELATIONSHIPS

4.1.1 Ground Water Travel Time

Ground water travel time through "heterogeneous" material is calculated by:

(3) $$t' = L / V' = L n' / (K' i)$$

which is the same as Equation 2, with the prime indicating that the parameter refers to the heterogeneous material.

The travel time which would be calculated from bulk properties is:

(4) $$t^* = L / V^* = L n^* / (K^* i)$$

which is also the same as Equation 2, with the asterisk indicating that the parameter refers to bulk properties.

4.1.2 Dimensionless Parameters

Dimensionless values can be developed for all the parameters. The general formula for a dimensionless variable is:

(5) $$X_D = \text{Parameter X}_{\text{(heterogeneous)}} / \text{Parameter X}_{\text{(bulk)}} = X' / X^*$$

A dimensionless parameter less than one would indicate that the "true" value of the parameter is less than the value based on bulk properties. The magnitude of the dimensionless parameter gives an indication of the relative error which would be associated with the use of bulk parameters.

4.1.3 Dimensionless GWTT

For the purpose of comparing results, dimensionless GWTT is defined as:

(6) $$t_D = t' / t^* = (n' / n^*) / (K' / K^*) = n_D / K_D$$

where: t_D = dimensionless GWTT

K_D = dimensionless hydraulic conductivity

n_D = dimensionless effective porosity

4.2 RESULTS

Equation 6 clearly indicates that uncertainties in both the hydraulic conductivity and effective porosity of materials within flow interiors will have an important impact on the GWTT. If it is assumed that the difference in effective porosity between typical and heterogeneous material is small (i.e., $n_D = 1$), then the GWTT relationship is:

(7) $$t_D = 1 / K_D$$

The contrast between the bulk hydraulic conductivity and the highest (heterogeneity) conductivity is expected to be many orders of magnitude, based on current concepts and data. Thus, K_D is likely to have a very large value. As a result, the "shortest travel time" would also be expected to be many orders of magnitude less than the value computed by using the bulk hydraulic conductivity.

It has been frequently hypothesized that there is a relationship between porosity and hydraulic conductivity for jointed rock (Snow, 1968; Sharp and Maini, 1972). If this relationship exists, it would be expected to be of the form:

(8) $$n = a K^b$$

where a and b are fitting parameters. The value of "b" is generally considered to be around 0.5 for rock.

Assuming, for the moment, that a similar relationship exists for effective porosity and that the fitting parameters "a" and "b" are the same for all basalt joint systems, substituting the above relationship into Equation 6 gives:

(9) $t_D = 1 / K_D^{(1-b)}$

If "b" is equal to unity (effective porosity directly proportional to hydraulic conductivity) then heterogeneity does not matter, as the travel time is the same for all sets of parameters. However, if "b" is less than unity, as is expected, then the travel time is inversely related to hydraulic conductivity, with higher heterogeneity hydraulic conductivities leading to lower travel times. Accordingly, it is probably nonconservative to use the bulk hydraulic conductivity to estimate travel time through a flow interior containing heterogeneities.

5.0 CONCLUSIONS

It is expected that calculations of GWTT based on bulk hydraulic conductivity will result in overestimating GWTT if high permeability heterogeneous features exist within flow interiors. Depending on the hydraulic conductivity and effective porosity contrast between different materials within the flow interior, and the relationships between these parameters, the errors associated bulk property travel times can be many orders-of-magnitude. From the standpoint of evaluating the GWTT criteria, calculations based on bulk properties are likely to be nonconservative and may lead to erroneous conclusions regarding regulatory GWTT performance criteria.

6.0 DISCUSSION

To date, considerable emphasis has been placed by DOE and NRC on using pre-emplacement ground water travel time as an indication of site suitability. However, due to a lack of data, travel time calculations have generally assumed that flow interiors are homogeneous with respect to hydraulic properties. As a result of analyses performed in this study, Terra Therma concludes that if heterogeneity exists within flow interiors, the GWTT Criterion, assessed on the basis of bulk properties, is subject to considerable uncertainty and may lead to erroneous conclusions regarding site suitability.

Terra Therma questions the feasibility of realistically evaluating the component of GWTT that can be relied upon for the flow interior of the emplacement and/or adjacent horizons. Accordingly, it does not at present seem reasonable for the NRC to require that DOE expend additional effort on the characterization of the heterogeneity of interiors based on the need to define the GWTT component resulting from flow within dense interiors.

However, it would seem prudent for the NRC to attempt to establish whether DOE proposes to take significant credit for the flow interior travel time component, as the NRC's verification of this credit will require detailed knowledge of the higher permeability features within the interior(s). This verification process would require data that is unlikely to be available prior to the excavation of a significant portion of the repository, and could therefore have a significant impact on the site characterization activities that would be needed for licensing.

7.0 REFERENCES

Gephart, R.E., et al. 1983. Geohydrologic Factors and Current Concepts Relevant to Characterization of a Potential Nuclear Waste Repository Site in Columbia River Basalt, Hanford Site, Washington. Rockwell Hanford Operations, RHO-BW-SA-326P.

Sharp, J.D. and Maini, Y.N.T. 1972. Fundamental Considerations on the Hydraulic Characteristics of Joints in Rock. Proc. ISRM Symposium on Percolation Through Fissured Rock, Stuttgart, pp. 1-15.

Snow, D.T., 1968. Rock Fracture, Spacings, Openings, and Porosities. Proc. ASCE, Jour. Soil Mech., Foundation Division, , vol. 94, no. SM 1, pp. 73-91.