Mini-Report #2

ANALYSIS OF FLOW
INTERIOR HETEROGENEITY:
CUMULATIVE FLUX

Basalt Waste Isolation Project
Subtask 2.5
Numerical Evaluation of Conceptual Models

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for

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

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 the EPA Cumulative Flux Standard?

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 regulatory criteria for site performance.

1.2 RELEVANCE TO NRC

Subpart E of 10 CFR Part 60 requires that the cumulative radionuclide flux reaching the accessible environment after permanent closure does not exceed the EPA Standard (40 CFR Part 91).

The EPA Standard addresses the cumulative flux of radionuclides across the boundary of the accessible environment over time periods of up to 10,000 years. Because ground water volumetric flux rate is directly proportional to hydraulic conductivity, the mass flux of radionuclides will be affected by the distribution of formation permeability.

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 cumulative radionuclide flux.

To date, relatively little information exists on the hydraulic/transport 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, vertical radionuclide flux 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 radionuclide flux to the heterogeneity of basalt flow interiors.

3.0 EVALUATION

3.1 OPERATIONAL APPROACH

The general approach to evaluating the sensitivity of cumulative flux to basalt flow interior heterogeneity is to consider the degree to which heterogeneity affects flux 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 warrented. If, on the other hand, 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

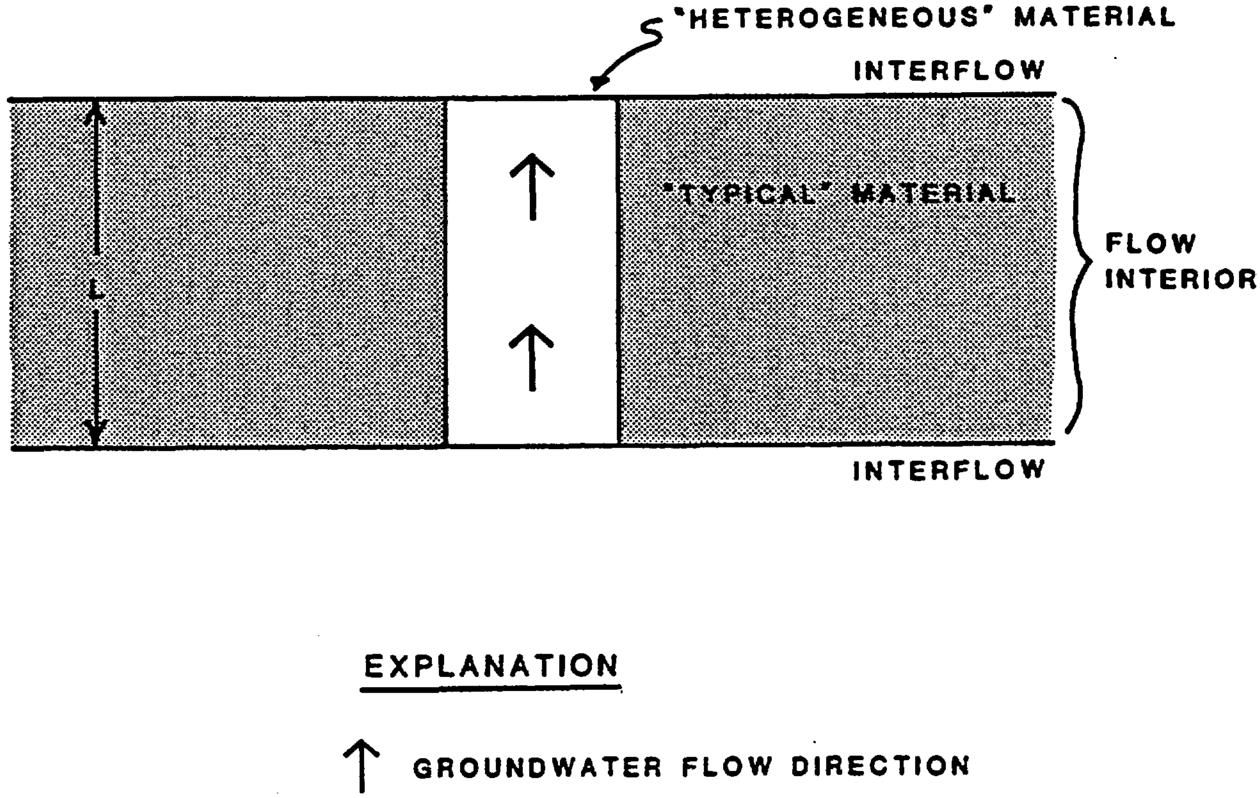
Basalt flow interiors are considered to control vertical flow (leakage) between adjacent interflows. Flow interiors are generally characterized by colonnade and entablature jointing with a preferred vertical orientation. However, a variety of internal structures, generally related to the pattern and 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 is regularly distributed and 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.

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



In evaluating the EPA criteria, each material type within the flow interior is treated as an equivalent porous medium with conditions appropriate for application of Darcy's law. For flux calculations, it is assumed that radionuclides act as conservative tracers without dispersion. Thus, radionuclide flux is directly proportional to the ground water flux.

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 cumulative radionuclide flux 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

Ground water travel time 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

Minimum travel time time through the flow interior is related to velocity occurring in the most permeable (heterogeneous) material.

Ground water volumetric flux rate is determined from another expression of Darcy's law:

$$Q = K A i \tag{2}$$

where: Q = volumetric flux rate

A = cross-section area normal to flow direction

When considering actual flow interior heterogeneity, net flux rate is equal to the sum of flow occurring witnin both typical and heterogeneous materials. For calculations based on integrated properties, bulk vertical conductivity is used in Equation 2.

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. Hydrodynamic dispersion and chemical retardation are not considered and radionuclides are treated as conservative tracers. Thus, radionuclide travel time is assumed equal to ground water travel time. Radionuclide flux rate is assumed proportional to ground water flux rate.

5. 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.

6. Hydraulic conductivity is the only parameter which varies spatially within the flow interior. Effective porosity, hydraulic gradient, and flow interior thickness are treated as constants.

7. Heterogeneous materials are regularly distributed (according to an assumed geometric model) and extend completely across the flow interior.

8. Bulk vertical hydraulic conductivity is assumed 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 geometric model shown in Figure 2. In planimetric view, the flow interior is considered to be composed of "typical" material (of relatively low hydraulic conductivity) and "heterogeneous" material (of higher conductivity). The model assumes that heterogeneous materials are square-shaped in cross-section (columnar in three dimensions) and uniformly spaced in a grid pattern.

4.1 BASIC RELATIONSHIPS

4.1.1 Ground Water Travel Time

Ground water travel time through "heterogeneous" material is calculated as follows:

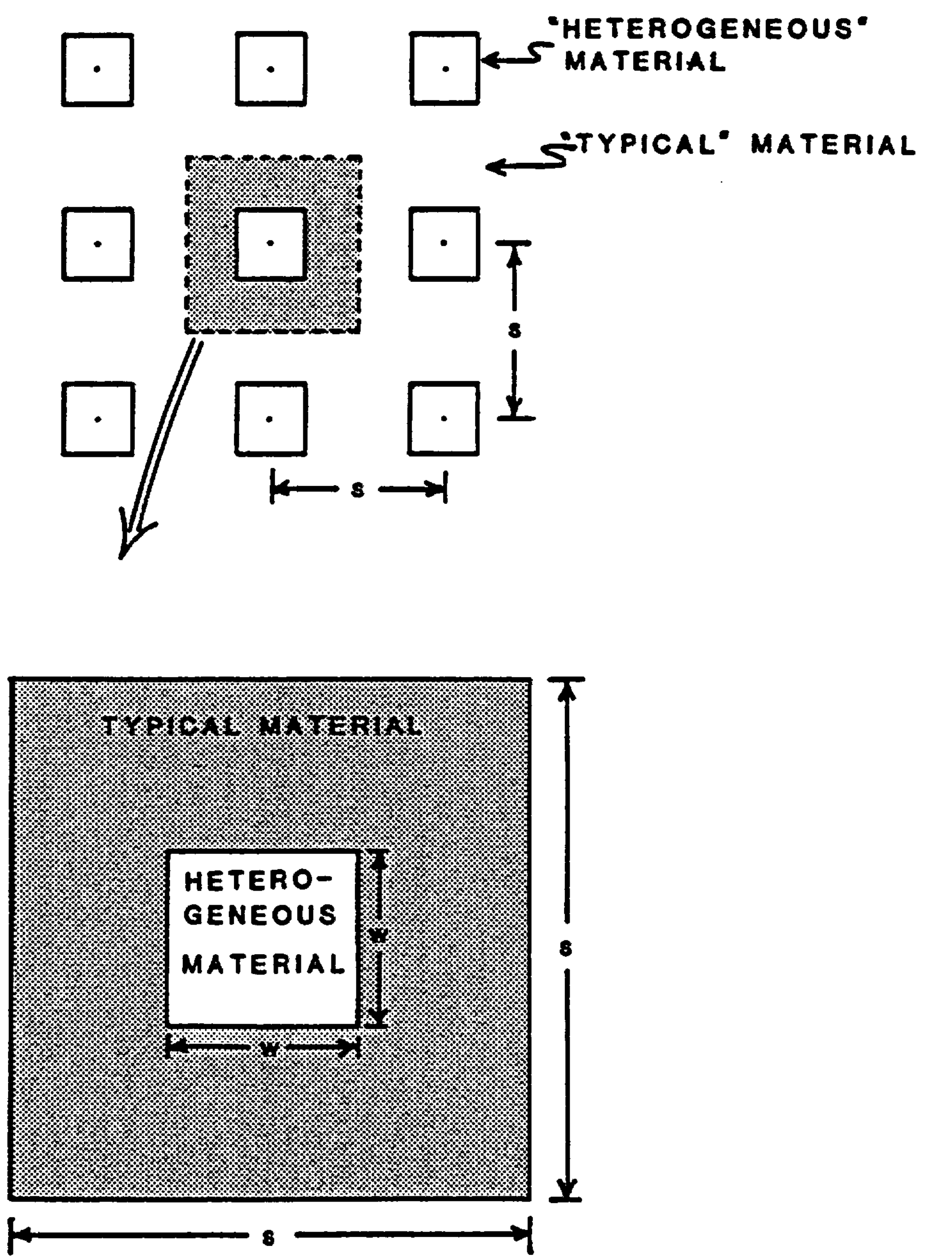
$$t_1 = L / V_1 = L\, n / (K_1\, i) \tag{3}$$

where:
t_1 = travel time through heterogeneous material
v_1 = flow velocity in heterogeneous material
L = flow interior thickness
K_1 = heterogeneous material hydraulic conductivity

and other parameters are defined previously.

FIGURE 2. GEOMETRIC MODEL OF FLOW INTERIOR HETEROGENEITY

(PLANIMETRIC VIEW)



In an analogous manner, ground water travel time through "typical" material is calculated by:

(4) $t_2 = L / V_2 = L n / (K_2 i)$

where: t_2 = travel time through typical material

V_2 = flow velocity in typical material

K_2 = typical material hydraulic conductivity

Minimum travel time through the flow interior is that occurring in the heterogeneous (highest velocity) material. Thus, t_1 calculated by Equation 3, is the relevant value.

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

(5) $t_B = L n / (K_B i)$

where: t_B = travel time based on bulk properties

K_B = bulk hydraulic conductivity

4.1.2 Ground Water Flux Rate

Ground water volumetric flux rate through heterogeneous material is calculated from the following equation:

(6) $Q_1 = K_1 A_1 i$

where: Q_1 = flux rate through heterogeneous material

A_1 = cross-sectional area of heterogeneous material

Volumetric flux rate through typical material is given by:

(7) $$Q_2 = K_2 A_2 i$$

where: Q_2 = flux rate through typical material

A_2 = cross-sectional area of typical material

The flux rate which would be calculated using bulk parameter properties is:

(8) $$Q_B = K_B A_B i$$

where: Q_B = calculated bulk flux rate

K_B = bulk vertical hydraulic conductivity

A_B = bulk cross-sectional area

In Equation 8, bulk cross-sectional area is:

(9) $$A_B = A_1 + A_2$$

and bulk hydraulic conductivity is related to the individual conductivities as follows:

(10) $$K_B = (K_1 A_1 + K_2 A_2) / (A_1 + A_2)$$

For the geometric model shown in Figure 2, the following relations hold:

(11) $$A_1 = w^2$$

(12) $A_2 = s^2 - w^2$

(13) $A_B = s^2$

where: s = spacing between heterogeneous features

w = width of heterogeneous features

4.2 DIMENSIONLESS PARAMETERS

For the purpose of comparing results, the following dimensionless quantities are defined as the ratio of a true value divided by the analogous value which would be calculated using bulk properties. Thus,

(14) $t_D = t / t_B$

(15) $Q_D = Q / Q_B$

where: t_D = dimensionless time

t = actual time

t_B = travel time through flow interior based on bulk properties

Q_D = dimensionless flow rate

Q = actual flow rate

Q_B = flow rate based on bulk properties

A dimensionless parameter greater than one would indicate that the actual value of the parameter is greater than the value which would be calculated using bulk properties. The magnitude of the dimensionless parameter gives an indication of the relative error which would be associated with the bulk value. For example, a Q_D value equal to 2 is interpreted to mean that the actual flow rate is two times greater than the flow rate which would be calculated using bulk hydraulic conductivity.

Additional dimensionless parameters are:

(16) $$W_D = w / s$$

(17) $$K_D = K_1 / K_2$$

where: W_D = dimensionless width of heterogeneous features

K_D = dimensionless hydraulic conductivity (contrast between heterogeneous and typical material)

The maximum value of W_D is 1.0, which represents a situation where all of the flow interior is made up of heterogeneous material (i.e., area of heterogeneous material is equal to the bulk area).

4.2.1 Dimensionless Travel Time

Dividing Equation 3 by 5 and substituting Equations 10, 11, 12, 16, and 17, the dimensionless travel time through heterogeneous material is given by:

(18) $$t_{D1} = W_D^2 + (1/K_D)(1 - W_D^2)$$

Dividing Equation 4 by 5 and substituting Equations 10, 11, 12, 16, and 17, the dimensionless travel time through typical material is:

(19) $t_{D2} = W_D^2 (K_D - 1) + 1$

4.2.2 Dimensionless Flux Rate

Dimensionless flux rate, at the flow interior boundary opposite to the radionuclide source, must be considered for three time periods. For dimensionless time less than or equal to t_{D1}, dimensionless flux rate is zero. This corresponds to the time period during which radionuclides have not yet traveled through the entire thickness of heterogeneous material. Thus:

(20) $Q_{D0} = 0 \; ; \quad \text{for:} \; t_D \leq t_{D1}$

For dimensionless time greater than t_{D1} and less than or equal to t_{D2}, dimensionless flux rate is determined by dividing Equation 6 by 8 and substituting Equations 9, 10, 11, 12, 16, and 17:

(21) $Q_{D1} = K_D W_D^2 / t_{D2} \; ; \quad \text{for:} \; t_{D1} < t_D \leq t_{D2}$

This corresponds to the time period during which radionuclides exit from flow interior only from heterogenous material. Radionuclides within typical material have not yet traveled through the entire flow interior thickness.

Finally for dimensionless time greater than t_{D2}, radionuclides exit from both heterogeneous and typical material and net flux rate is equal to the sum of rates from each material. Dimensionless flux rate from heterogeneous material is given by Equation 21 and flux rate from typical material is determined by dividing Equation 7 by 8 and substituting 9, 10, 11, 12, 16, and 17. After performing the appropriate mathematical operations, it is discovered that this flux rate is exactly equal to the bulk flux rate. Thus:

(22) $$Q_{D2} = 1 \; ; \quad \text{for: } t_D > t_{D2}$$

4.2.3 Dimensionless Cumulative Flux

Dimensionless cumulative flux is proportional to the net flux of radionuclides which have exited from the flow interior (opposite from the source boundary) during a given time. It is defined by the following equation:

(23) $$V_D = \int_0^{t_D} Q_D \, dt_D$$

where: V_D = dimensionless cumulative flux

By making the appropriate substitutions, dimensionless cumulative flux for the three cases given in Section 4.2.2 is:

(24) $$V_D = 0 \quad ; \text{ for: } t_D \leq t_{D1}$$

(24) $$V_D = Q_{D1}\,(t_D - t_{D1}) \quad ; \text{ for: } t_{D1} < t_D \leq t_{D2}$$

(25) $$V_D = Q_{D1}\,(t_{D2} - t_{D1}) + (t_D - t_{D2}) \; ; \text{ for: } t_D > t_{D2}$$

To provide a means of comparison, the dimensionless cumulative flux which would be predicted based on bulk hydraulic conductivity is:

(26) $V_{DB} = 0$; for: $t_D \leq 1$

(27) $V_{DB} = t_D - 1$; for: $t_D > 1$

where: V_{DB} = dimensionless cumulative flux based on bulk hydraulic conductivity

In Section 4.3, the effect of heterogeneity on the EPA standard is evaluated by comparing V_D and V_{DB} as functions of t_D.

4.3 RESULTS

Using equations 24, 25, and 26, a series of plots have been prepared (Figures 3 to 7) showing dimensionless cumulative flux vs. dimensionless time for various values of K_D and W_D. For comparison, the dimensionless cumulative flux which would be calculated using bulk properties (equations 26,27) is also shown on each plot. The error between cumulative fluxes based on actual and bulk properties is small for the following parameter ranges:

- For K_D equal to one (Figure 3). This is expected because a K_D value of unity would indicate that there is no permeability contrast between heterogeneous and typical materials. Thus, the flow interior would be homogeneous with an actual hydraulic conductivity equal to the bulk conductivity value.

FIGURE 3. DIMENSIONLESS CUMULATIVE FLUX VS. DIMENSIONLESS TIME FOR DIMENSIONLESS HYDRAULIC CONDUCTIVITY EQUAL TO 1

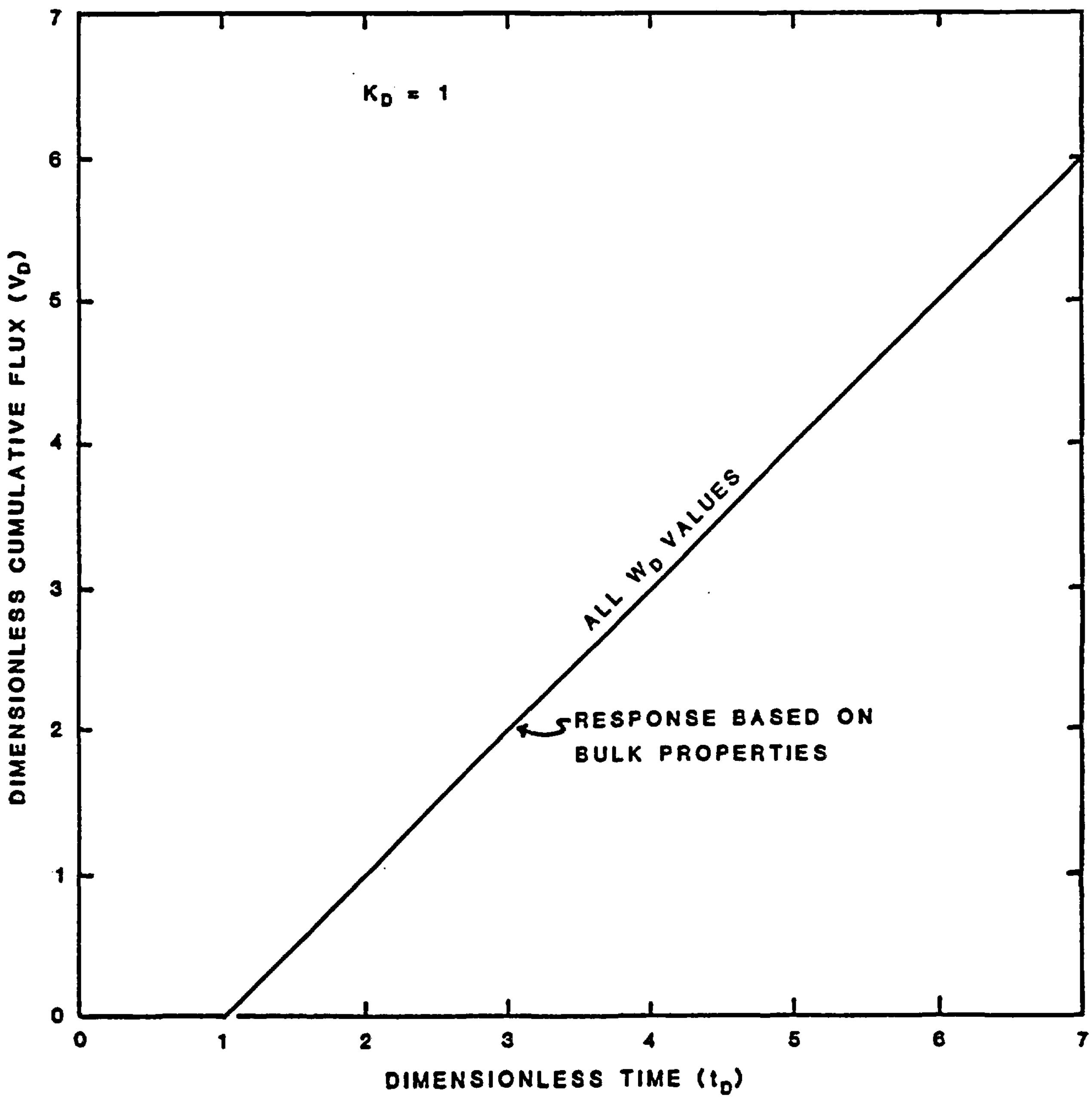


FIGURE 4. DIMENSIONLESS CUMULATIVE FLUX VS. DIMENSIONLESS TIME FOR DIMENSIONLESS HYDRAULIC CONDUCTIVITY EQUAL TO 10^2

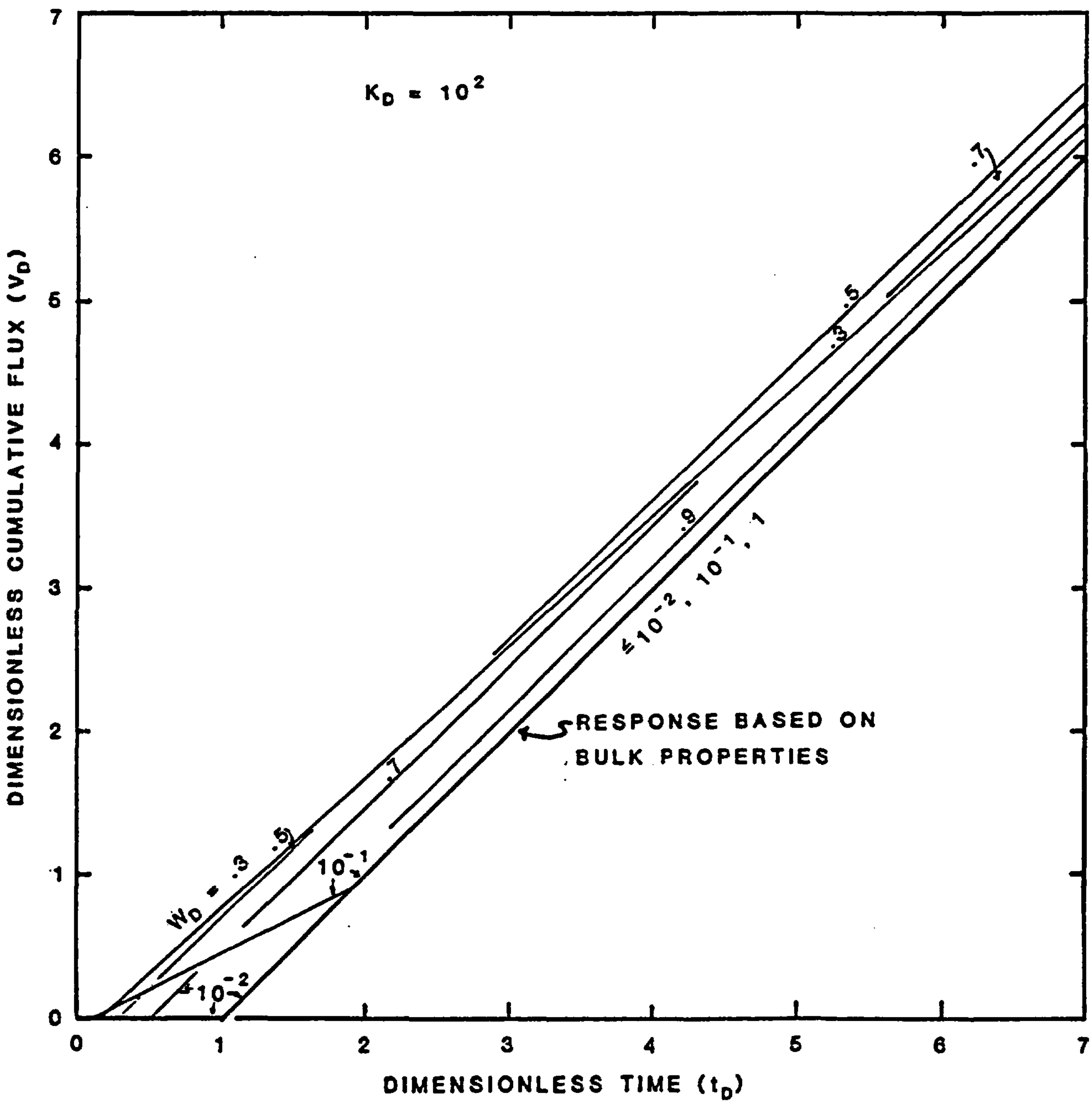


FIGURE 5. DIMENSIONLESS CUMULATIVE FLUX VS. DIMENSIONLESS TIME FOR DIMENSIONLESS HYDRAULIC CONDUCTIVITY EQUAL TO 10^4

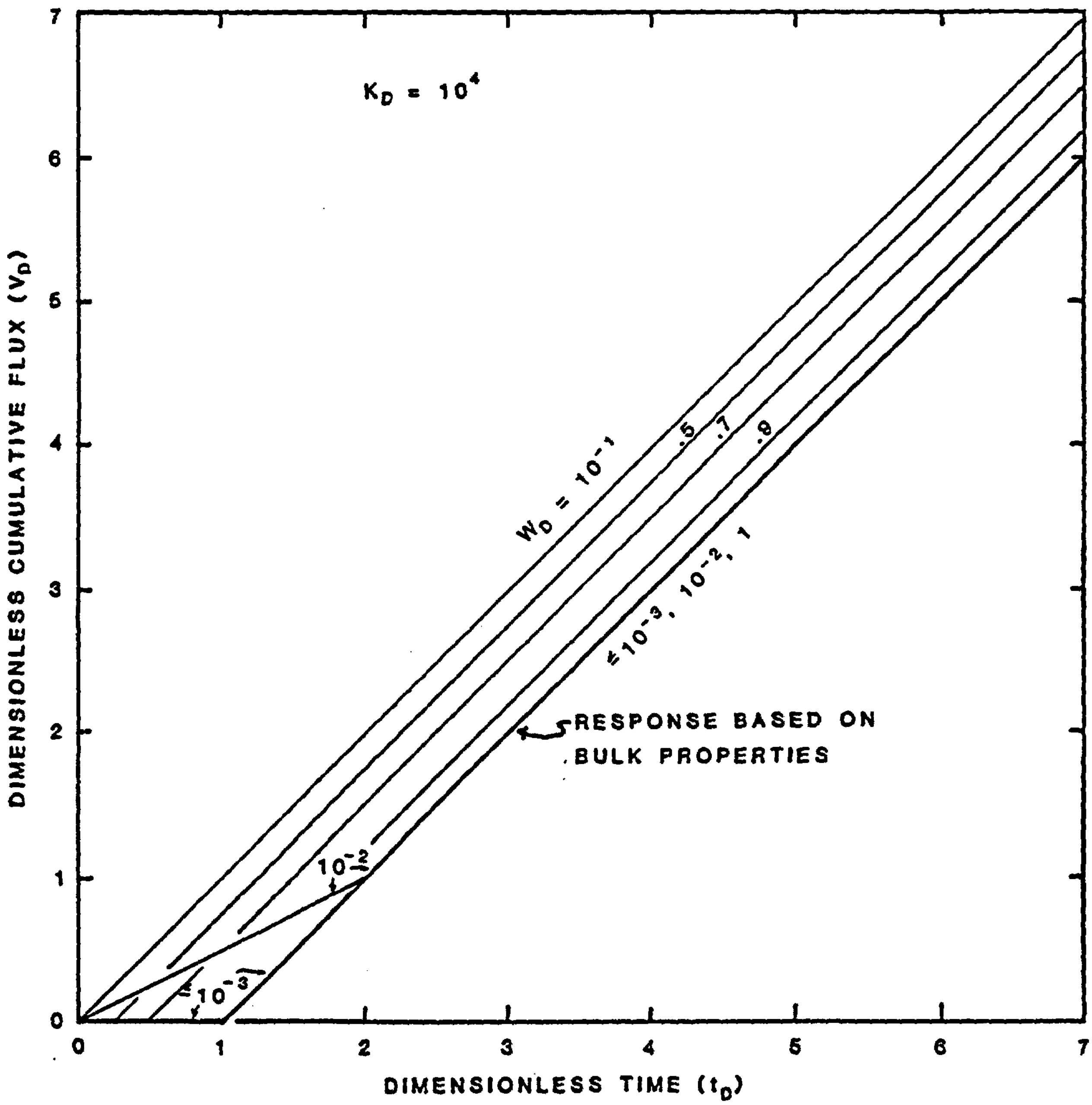


FIGURE 6. DIMENSIONLESS CUMULATIVE FLUX VS. DIMENSIONLESS TIME FOR DIMENSIONLESS HYDRAULIC CONDUCTIVITY EQUAL TO 10^6

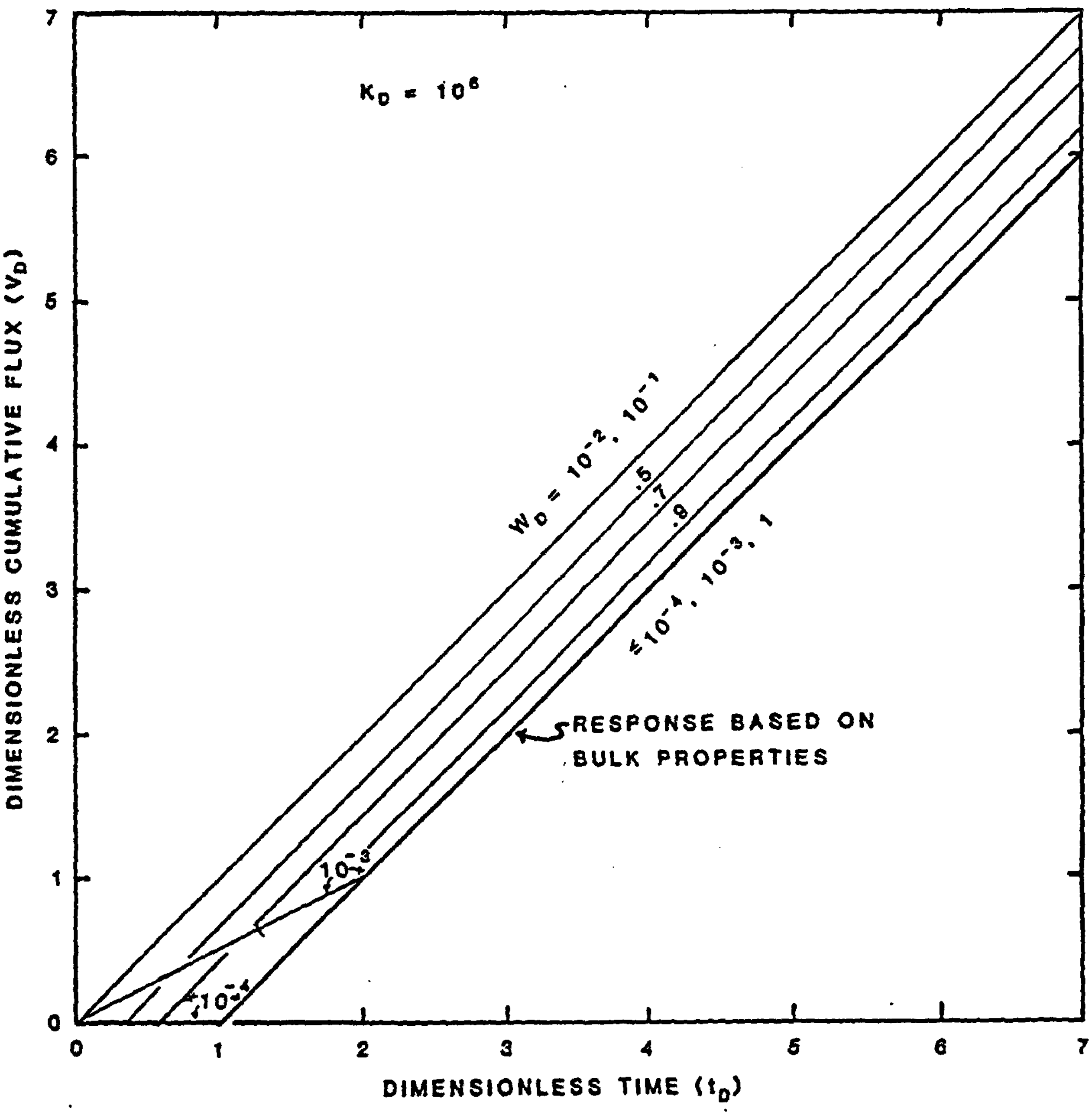
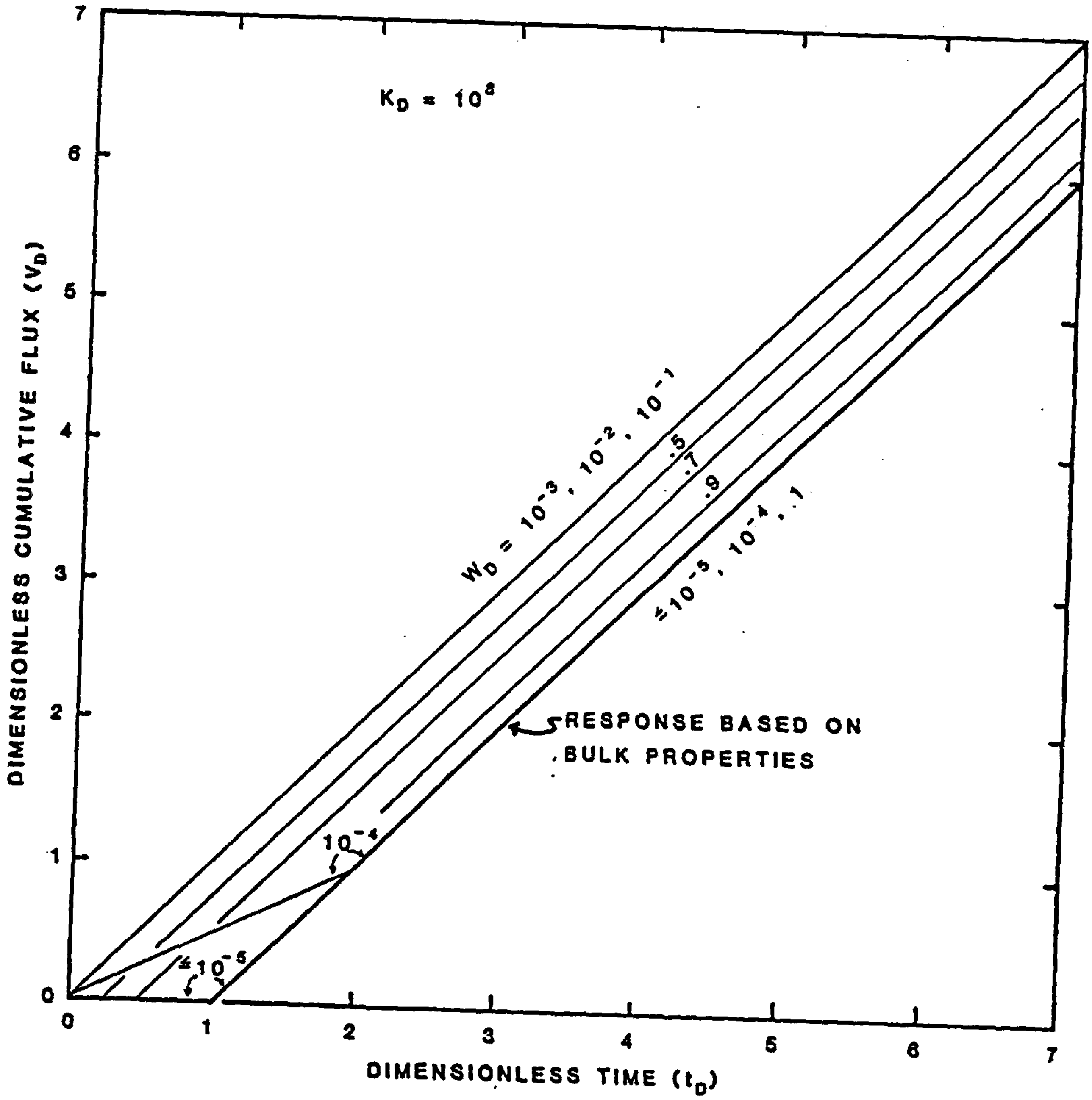


FIGURE 7. DIMENSIONLESS CUMULATIVE FLUX VS. DIMENSIONLESS TIME FOR DIMENSIONLESS HYDRAULIC CONDUCTIVITY EQUAL TO 10^8



- For small W_D values. In this case, the cross-sectional area of heterogenous features is insufficient to substantially increase the net flux through the flow interior. Based on Figures 4 to 7, the following empirical equation has been developed to indicate situations where heterogeneity would not significantly affect evaluation of the EPA Standard:

(28) $$\log(W_D) < -\log(K_D) / 2 - 1 ; \quad \text{for: } K_D > 10^2$$

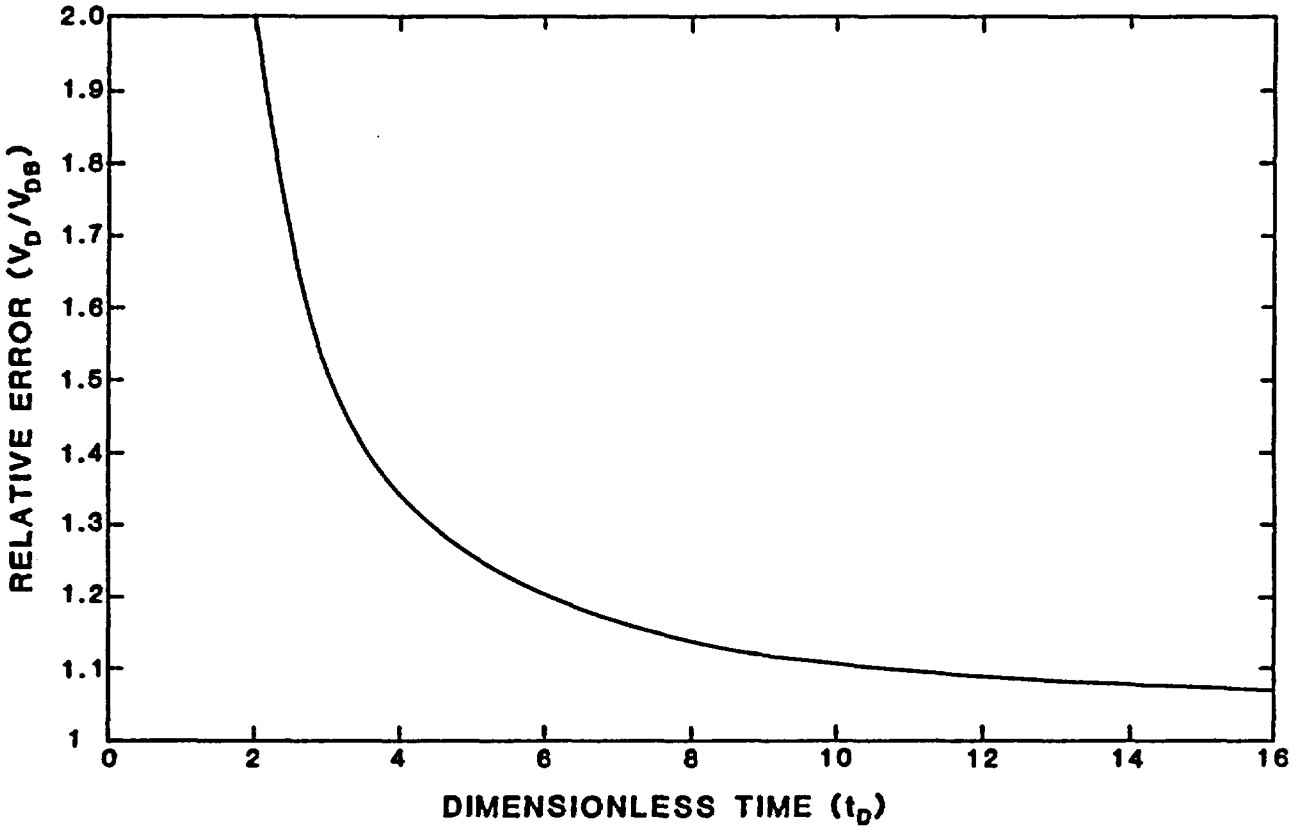
- As W_D approaches 1.0. This indicates a situation where the flow interior becomes homogeneous, being composed entirely of "heterogeneous" material. In this case, bulk hydraulic conductivity would approach the conductivity of heterogeneous material. Thus, cumulative flux based on bulk properties would be approximately equal to the actual cumulative flux.

- At larger dimensionless times, some intermediate W_D values result in cumulative flux curves that approach or equal the cumulative flux based on bulk properties. The conditions under which this occurs can be seen in Figures 4 to 7.

It is interesting to note in Figures 3 to 7 that the maximum difference between actual dimensionless cumulative flux and flux based on bulk properties is equal to one. Thus, as dimensionless time increases, the relative error between the two fluxes becomes less significant and cumulative flux based on bulk properties becomes more reliable in evaluating the EPA Standard.

In Figure 8, the maximum value of the ratio (V_D/V_{DB}) is plotted for t_D greater than 2. For t_D greater than 6, the error associated with cumulative flux based on bulk properties is no more than 20 percent ($V_D/V_{DB} < 1.2$) for all values of K_D and W_D. Thus, for large values of dimensionless time, the uncertainty associated with flow interior heterogeneity will probably be small compared to other uncertainties involved in evaluating cumulative flux rates. However, at small values of dimensionless time, use of bulk properties may lead to significant underestimates of cumulative flux rate, which would be nonconservative for evaluating the EPA Standard.

FIGURE 8. RATIO OF ACTUAL CUMULATIVE FLUX TO FLUX BASED ON BULK PROPERTIES FOR DIMENSIONLESS TIME GREATER THAN 2.



5.0 CONCLUSIONS

As discussed in Section 4.3, heterogeneity can result in an underestimation of cumulative radionuclide flux, if calculations are based on bulk hydraulic properties. However, for many combinations of hydraulic/geometric parameters, the errors associated with bulk property flux rates are small or negligible compared to other uncertainties involved in the calculations. With regard to evaluating the EPA Standard, heterogeneity may be a less significant concern (compared to the GWTT criterion), provided that sufficient information is available to assess magnitude of associated errors.

6.0 DISCUSSION

The results of this study suggest that under many possible conditions existing at the BWIP site, evaluation of the EPA Standard may not be sensitive to flow interior heterogeneity. Analyses performed herein provide some guidance in assessing the conditions under which heterogeneity can be safely ignored. Terra Therma therefore recommends that the EPA Cumulative Release Criterion be up-graded as a site performance standard, because it is probably a more robust measure of site performance with respect to flow interior heterogeneity.

Hydrologic characterization of flow interior heterogeneity should be approached in a phased manner. If initial data indicate that cumulative flux calculations will not be sensitive to flow interior heterogeneity, then additional site characterization will need to concentrate only on measuring bulk properties (which can probably be done more quickly and at a lower cost). However, if flux calculations are sensitive to heterogeneity, detailed characterization of flow interiors may be required.

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.