BWIP Mini-Report #4

RELATIONSHIP OF HYDRODYNAMIC DISPERSION TO COMPLIANCE WITH OVERALL EPA RELEASE STANDARDS

Basalt Waste Isolation Project
Subtask 2.5
Numerical Evaluation of Conceptual Models

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for

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1.0 INTRODUCTION

1.1 PUBLIC LAW 97-425 (NWPA)

Public Law 97-425, the Nuclear Waste Policy Act of 1982 (NWPA), establishes the framework for the development of the national program for the disposal of high-level nuclear waste in the United States. Important aspects of NWPA address the roles and responsibilities of the major parties in the process and the schedule for selecting and developing a repository. For the purposes of this report, the major parties and their roles in the process include:

1. The U.S. Environmental Protection Agency (EPA). EPA is responsible for establishing generally applicable environmental standards for radioactivity (40 CFR 191).

2. The U.S. Department of Energy (DOE). DOE is responsible for selecting potentially acceptable sites, conducting site characterization and performance confirmation studies, preparing and defending a license application for a geologic repository system, constructing, operating and ultimately decommissioning a licensed repository.

3. The U.S. Nuclear Regulatory Commission (NRC). The NRC is responsible for providing guidance to DOE on acceptable elements of a site characterization and licensing program, reviewing DOE's Site

Characterization Plans, reviewing DOE's license application, and licensing the construction and operation (including permanent closure and decommissioning) of the repository.

1.2 REGULATORY FRAMEWORK

It is the position of TTI that for the purposes of hydrogeologic reviews conducted by the NRC staff, relevance can be established only with reference to the regulations that the staff are directed to apply, that is, 10 CFR Part 60 and 40 CFR Part 191. The purpose of this section is to identify the relevant portions of these regulations. We consider that this is a necessary step in formulating and constraining conceptual models at BWIP or at any other site.

1.2.1 Subpart E, 10 CFR Part 60

Principal portions of Subpart E of 10 CFR Part 60 that require technical assessment include:

(1) Through Permanent Closure

- 60.111(a), limiting radiation exposures and releases of radioactive material during operations.
- 60.111(b), requiring the option of waste retrieval be preserved during operations.

(2) After Permanent Closure

- 60.112, limiting releases of radioactive materials to the accessible environment (also limiting radiation exposures and concentrations of radionuclides in special sources of groundwaters) after permanent closure to those permitted by the EPA standard (40 CFR Part 191).

- 60.113(a)(1)(ii)(A), requiring a minimum waste package containment time.

- 60.113(a)(1)(ii)(B), limiting the radionuclide release rate from the engineered barrier system.

- 60.113(a)(2), addressing minimum pre-emplacement groundwater travel time from the disturbed zone to the accessible environment.

- 60.122, addressing favorable and potentially adverse siting conditions.

- 60.131 - 60.135, addressing design criteria.

For each of the post-closure subsystem performance objectives (i.e., waste package containment, release rate from the engineered barriers, and pre-emplacement groundwater travel time), the final rule provides for flexibility in the regulation by permitting DOE to propose and the Commission to accept a lower subsystem performance goal provided that DOE can demonstrate with reasonable assurance that the overall system meets the EPA standard.

1.2.2 The EPA Standard

Section 112 of 10 CFR Part 60 requires DOE to demonstrate that the applicable EPA Standard will be met for the overall repository system performance. Subpart B of 40 CFR Part 191 establishes several different types of requirements:

- 191.13, limiting cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal.
- 191.14, describing qualitative assurance requirements.
- 191.15, limiting radiation doses to individuals for 1,000 years after disposal for cases of undisturbed performance.
- 191.16, limiting the radionuclide concentrations in special sources of groundwater for 1,000 years after disposal for cases of undisturbed performance.

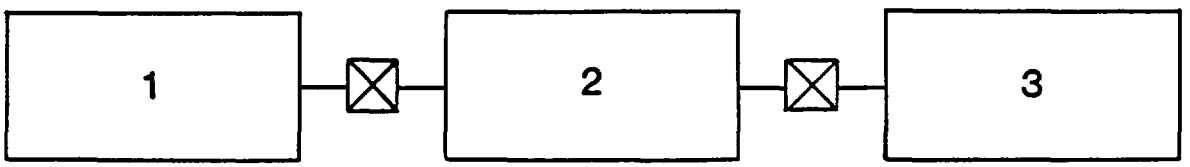
For definitions of terms and discussion of the details of 40 CFR Part 191, consult Federal Register, v. 50 no. 181, Thursday Sept. 19, 1985, p. 38066-38089. For discussion of the NRC staff position on the applicability of the EPA standard to NRC licensing reviews, consult Draft Generic Technical Position on Licensing Assessment Methodology, April 30, 1984.

1.3 GENERAL STATEMENT OF THE PROBLEM

To address compliance with the overall EPA Standard (40 CFR 191.13), the performance measure is cumulative release of radioactivity across a hypothetical boundary in 10,000 years. In order to predict the release of radionuclides to the accessible environment (for a given source term and site hydrogeology) there must be an evaluation of the transport of radionuclides through the flow system of the site.

The standard approach to the description of transport of solutes in groundwater is to consider the flux of solutes into and out of a fixed reservoir (often considered to be some elemental volume) within the flow domain. One can consider the release of solutes from a high-level nuclear waste (HLW) repository to the accessible environment in terms of a simple arrangement of reservoirs and material transfer between them (Figure 1). Reservoir 1 can be considered to be the engineered barrier system (EBS), Reservoir 2 to be the subsurface portion of the controlled area, and Reservoir 3 to be the accessible environment, where Reservoir 2 may be either accumulating or non-accumulating.

Figure 1 Reservoirs For Mass Transport



Conservation of mass requires that:

$$(1) \quad \frac{d\, m_2^i}{d\, t} = {}_2J_3^i - {}_1J_2^i \; +/- \; \Delta\, m_c^i$$

where m_2^i is the mass of solute i in Reservoir 2,

${}_2J_3^i$ is the flux of solute i out of Reservoir 2,

${}_1J_2^i$ is the flux of solute i into Reservoir 2,

$\Delta\, m_c^i$ is the change in mass of solute i due to reactions within Reservoir 2,

t is time.

The flux of a solute into or out of a reservoir is controlled by physical processes (advection and hydrodynamic dispersion) and physico-chemical processes (chemical reactions and radioactive decay). The purpose of this mini-report is to analyze the importance of a detailed knowledge of hydrodynamic dispersion to the computation (or prediction) of cumulative releases of radionuclides to the accessible environment. The subset of flow and transport conditions described in this mini-report is steady, one-dimensional, advective-dispersive transport of a single non-reactive constituent in a saturated, isotropic, porous medium.

There are two major reasons for addressing this matter in detail at this time. First, BWIP is preparing to move into the Site Characterization phase of investigations, including the development of a large-scale hydraulic testing program that includes a significant effort aimed at determining representative

values of dispersivity for the Hanford basalts. In addition to the practical aspects of resource commitment (by both DOE and NRC), there is a substantial controversy in the hydrogeologic community about the physical and mathematical formulation of dispersion, which some have proposed must be resolved before it would be possible to license a geologic repository for HLW (e.g., Gelhar, 1985).

1.4 RELATIONSHIP TO OTHER ANALYSES AND PRODUCTS

The NRC's Division of Waste Management has contracted with Nuclear Waste Consultants, Inc. (NWC) to provide technical assistance in hydrogeology for the three sites selected for site characterization. Task 2 - Reviewing the Hydrogeologic Investigations of BWIP - has been subcontracted to Terra Therma, Inc (TTI). Subtask 2.5 calls for analytical evaluations of aspects of conceptual flow and transport models developed for BWIP. Because the reports describing these modeling efforts are to be updated over the period of performance of the current contract, NWC and TTI have decided to issue a series of "mini-reports" which evaluate selected portions of the overall flow and transport systems which may exist at the site. This approach will allow subsequent reports to reference previously issued mini-reports instead of requiring complete (and sometimes redundant) theoretical development for each new topic.

2.0 OBJECTIVE

The objective of this report is to determine the sensitivity of cumulative releases of radionuclides to the accessible environment (40 CFR 191.13) to hydrodynamic dispersion in saturated basalt.

3.0 OPERATIONAL APPROACH

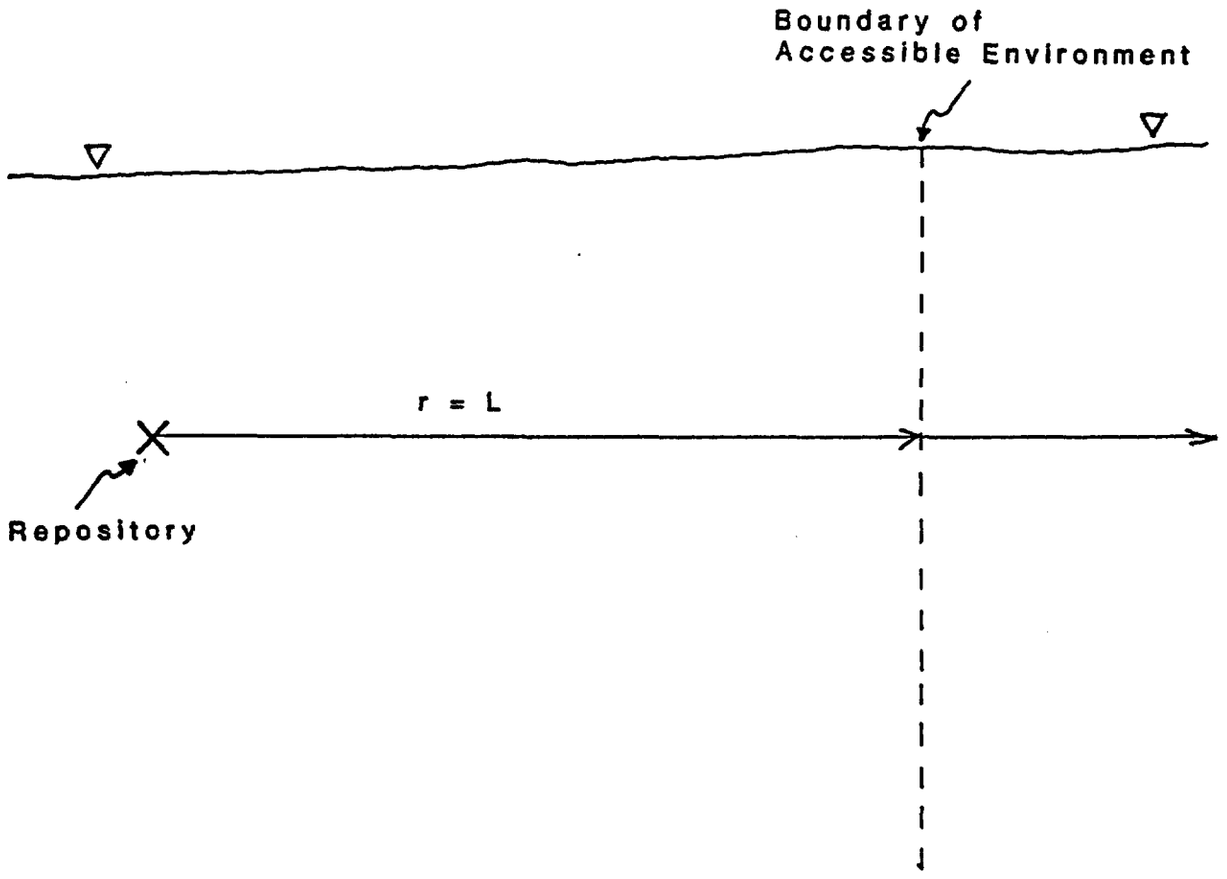
3.1 GEOLOGY

The general approach used in this analysis is independent of the geologic medium in which a repository may be located, so long as the repository is located in the saturated zone. For the purposes of this mini-report, the lithology can be considered as basalt similar in all respects to the basalts of the RRL.

3.2 CONCEPTUAL MODEL OF FLOW AND TRANSPORT

The framework of the conceptual model considered for radionuclide transport consists of a repository in a homogeneous, isotropic basalt which is semi-infinite in extent (Figure 2). For the purposes of this analysis, the repository is considered to be a point, representing the location of a point-source release of radionuclides. Because the EPA Rule defines the accessible environment in terms of a hypothetical boundary located at a fixed distance (not more than 5 km) from the boundary of the controlled area, the domain is radially symmetric, with a radius of L (which can be considered as 5 km). The use of a single basalt "layer", while not realistic as a conceptual model of the site, is a useful simplification equivalent to treating the first

Figure 2 Conceptual Model for Flow and Transport System



layer of a multiple-layer model: if one can address the problem for a single layer, then the multiple-layer problem can be addressed by superposition.

The flow regime is considered to be steady-state, Darcy flow through an equivalent porous medium (EPM) which is homogeneous and isotropic, and the flow system is modeled deterministically. The only assumption which is likely to be critical with respect to the general result is the assumption of Darcian flow. (The assumptions of homogeneity and isotropy, the focus of most of the controversy about various approaches to evaluating macrodispersion, are implicit in all available methods of analyzing field tests for longitudinal dispersion. Thus, since any DOE testing program aimed at evaluating dispersion will be based on a model of a homogeneous, isotropic EPM, it is entirely appropriate to base this analysis on the same model.) The other assumptions lead to more complex formulations of the flow and transport equations, some of which would require numerical evaluation for computation of actual radionuclide fluxes, but they would not change the general form of the differential equation with respect to hydrodynamic dispersion.

For simplicity in computation, this analysis assumes that only one radionuclide is released and that the radionuclide behaves as a perfectly non-reactive tracer in the groundwater system. The use of a single radionuclide is equivalent to assuming that there are no significant physical or chemical interactions between the radionuclides that would increase the curie flux at the accessible boundary, an entirely reasonable assumption. The total flux of radionuclides would be addressed by superposition of independent

solutions. Considering the radionuclide as a non-reactive solute is clearly highly conservative, but is in any case irrelevant to the evaluation of dispersion, since chemical reaction and radioactive decay are mathematically addressed in the transport equation by a term that does not include dispersion. Thus, the sensitivity of cumulative releases to dispersion is independent of the reaction terms, and the analysis can neglect reaction without any loss of generality.

Because the tracer is assumed to be perfectly non-reactive, the flow field to be steady, and the input function to be instantaneous, conservation of mass requires that

$$(2) \qquad C(x,t) \geq C(x,y,t) \geq C(x,y,z,t) \quad \text{for all } (x,y,z,t) > 0,$$

where C is concentration of the radionuclide in solution,

x,y,z are Cartesian directions,

t is time.

Therefore, it is always conservative (as well as computationally convenient) to consider cumulative release as a one-dimensional problem. Note that although the one-dimensional problem is again not "realistic" for BWIP, because of the radial symmetry of the problem, any non-reactive solute that is dispersed laterally or vertically must also cross the boundary of the accessible environment, and so would be computed as part of the cumulative flux. Therefore, from the point of view of regulatory compliance, the one-dimensional analysis is fully adequate for qualification (though not

necessarily for disqualification, which might indicate a need for a multi-dimensional analysis). As with all the TTI and NWC analyses, the fundamental approach is to first try to solve a problem using the simplest possible method and to move on to more complex analyses if and only if a more simple analysis will not be adequate to reach a responsible decision.

3.3 REPOSITORY AND SOURCE TERM

Because the analysis is for a generalized solution to the one-dimension advective-dispersive equation for a single non-reactive solute, the repository is modeled as a point and the source-term is considered to be an instantaneous injection of concentration C_o. Conceptually, this is equivalent to considering the entire solubility-limited curie inventory to be available at a point due to simultaneous failure of all aspects of the engineered barrier system at 1,000 years. (Alternatively, one could take the 10^{-5} release rate limit instead of the solubility limit. While this assumption might lead to a different value of C_o, the value would still be a constant for a given calculation.)

4.0 TECHNICAL APPROACH

4.1 FORMAL STATEMENT OF PROBLEM

For the modeled system, the cumulative release of curies to Reservoir 3 of Figure 1 is given by:

(3) $$R = Q * C * t,$$

where R is the cumulative release of radioactivity (Ci),

Q is the flux of water from Reservoir 2 to Reservoir 3 (L/yr) (constant),

C is the integrated concentration of the radionuclide of interest at the boundary of Reservoir 3 (Ci/L),

t is time (yr).

4.2 ANALYSIS

The one-dimensional, advective-dispersive equation for non-reactive constituents in saturated, homogeneous, isotropic materials under steady-state, uniform flow is:

$$(4) \qquad \frac{\partial C}{\partial t} = D_x \frac{\partial^2 C}{\partial x^2} - \bar{v}_x \frac{\partial C}{\partial x}$$

where C is the solute concentration (Ci/L),

x is the longitudinal direction (m)

t is time (sec)

D_x is the coefficient of hydrodynamic dispersion in the x direction (m^2/s)

$\bar{v}_x$ is the average linear groundwater velocity in the x direction (m/sec) (Bear, 1972).

For boundary conditions:

$C(x,0) = 0 \qquad x \geq 0$

$C(0,t) = C_0 \qquad t \geq 0$

$C(\infty,t) = 0 \qquad t \geq 0,$

the solution to Equation (4) is

$$(5) \qquad \frac{C}{C_0} = 1/2 \left[1 - \text{erf} \frac{x - \bar{v}t}{2\sqrt{D_x t}} \right], \quad x + \bar{v}t > 0$$

where erf is the error function, $\text{erf } z = (2/\pi) \int_0^z \exp(-u^2) du$ (von Rosenberg, 1956; Bear, 1972).

(Note that this is equivalent to the Ogata and Banks (1961) solution presented in Freeze and Cherry (1979) (p. 391) for the identity $\text{erfc } z = (1 - \text{erf } z)$ and the assumption that distance and time are both large.)

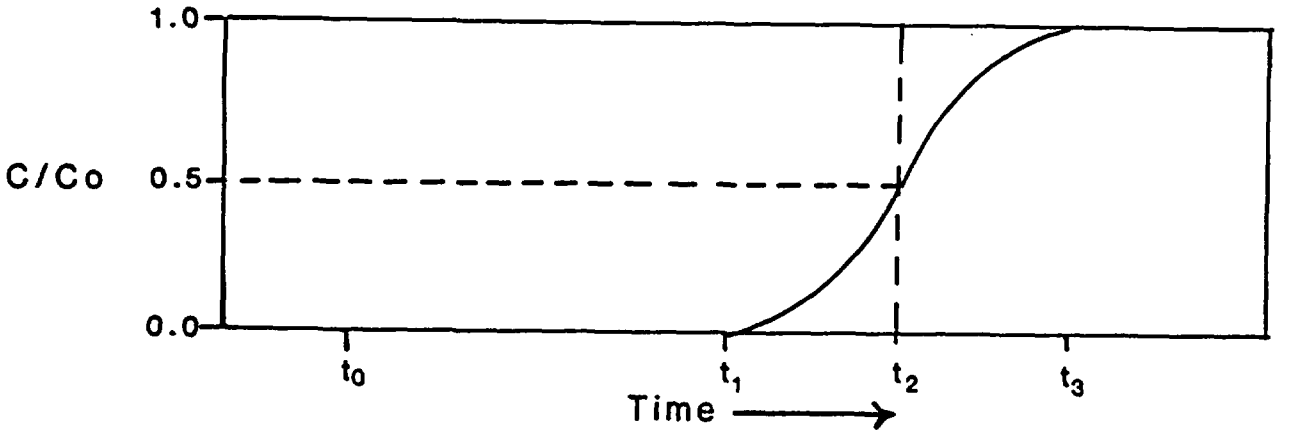
4.3 RESULTS

For any value of D_x and v_x, the (1 - erf z) solution produces a breakthrough curve at x = L of the form shown in Figure 3.

The cumulative concentration at point L is given by the product of the Darcy flux times the area under the breakthrough curve from t_1 to t_3, or

$$(6) \qquad R = Q * \int_{t_1}^{t_3} (C/C_0)\, dt.$$

Figure 3 Breakthrough Curve for One-Dimensional Advective-Dispersive System



There is no exact solution for an integral of the form of the error function. However, the error function, as its name implies, is based on the distribution of the standard error and is, therefore symmetrical about $C/C_0 = 0.5$. Therefore, the cumulative release is also equivalent to

(7) $$R = Q * C_0 * t_2.$$

Note that this relationship can now be extended to include the effects of reaction such as adsorption and radioactive decay:

(7') $$R' = Q * \left[C_0 * t_2 - 1/(\lambda K_d)\right],$$

where λ is the decay constant for the radionuclide of concern (1/sec)

K_d is the distriction coefficient for the radionuclide of concern (L/mg).

4.4 APPLICATION TO THE EPA STANDARD

For the condition that t_3 is less than or equal to 10,000 years, Equation 6 shows that the cumulative release of radioactivity to the accessible environment is (or can be predicted as if it were) independent of hydrodynamic dispersion, since it could be calculated reliably from knowledge of the Darcy flux, the average linear velocity, and the source term concentration.

Similarly, if the cumulative release predicted by Equation 7 (including the extended form of Equation 7' that includes the reaction terms for retardation

and decay) meets the EPA Standard, regardless of the relationship of t_2 to 10,000 years, then hydrodynamic dispersion can be neglected for the purpose of assessing compliance with 40 CFR 191.13.

It is hypothetically possible that there is a configuration of the breakthrough curve at L = 5 km for which R (computed by either Equation 7 or 7') fails to meet the EPA standard but for which R would meet the standard if Equation 6 were evaluated for

$$R'' = Q * \int_0^{10,000\ yrs} (C/C_0)\, dt. \qquad (6'')$$

This situation could arise if the spread of the solute front (the width of the "transition zone" in the terminology of Bear (1972)) were sufficient to dilute the dissolved radioactivity for a period of 10,000 years to the point where the cumulative flux in the regulatory time-frame were less than the standard.

From the form of Equation 5, it can be shown that the spread of the front is directly proportional to the square root of the average linear velocity and inversely proportional to the square root of the hydrodynamic dispersion (see also Bear, 1972, p. 585). Therefore at a given average linear velocity, the spread of the front increases as the square root of the average distance traveled. For the case of assessing compliance with the EPA standard, the distance of concern is specified to be 5 km, and the average distance traveled would have to exceed 5 km before the spread of the front would cause dilution sufficient to meet the test of Equation 6". For hydrodynamic dispersion to affect the shape of the breakthrough curve as much as does the average linear

velocity, D_x also must approach the square root of the average distance traveled. Therefore, for hydrodynamic dispersion to be signficant with respect to allowing a site to meet the EPA standard using Equation 6", hydrodynamic dispersion would have to be on the order of at least 2 km.

5.0 CONCLUSIONS

For the conditions considered in this analysis, prediction of cumulative releases of radioactivity to the accessible environment is not sensitive to hydrodynamic dispersion. Based on the analysis of one-dimensional transport of a non-reactive tracer, it has been shown that it is possible to predict the cumulative release of radioactivity to the accessible environment without any knowledge of hydrodynamic dispersion unless the calculated release fails both of two tests and hydrodynamic dispersion can be shown to exceed 2 km. The significance of this conclusion with respect to evaluating the proposed BWIP Large-Scale Hydraulic Stress Testing program is discussed in the next section.

6.0 DISCUSSION

6.1 HYDRODYNAMIC DISPERSION AND THE OVERALL EPA STANDARD

The testing and analysis of hydrodynamic dispersion is a standard part of most contaminant transport studies because for most contamination problems the regulatory test (and the appropriate performance measure based on potential health effects) is one of concentration over space and time (e.g., compliance with the MCL's of 40 CFR 264 or 40 CFR 192, Subparts D and E). In these cases, it is necessary to have a methodology for assessing C(x,t) with respect to C_o, such as is provided by the advection-dispersion equation.

However, in the case of the cumulative release requirement of the overall EPA Standard (40 CFR 191.13), the analysis presented here shows that a regulatory decision can be reached without any information on hydrodynamic dispersion for any combination of source term (C_o) and Darcy flux (and appropriate geochemical conditions) that meets the 10,000 year limit. It is clear that DOE must define the source term and the Darcy flux for the geologic repository system in order to have a complete license application. Depending on the results of site characterization (including engineering designs for the EBS), DOE may wish to take a certain amount of credit for geochemical retardation of radionuclides in order to provide reasonable assurance that the cumulative releases to the accessible environment over 10,000 years will meet the EPA Standard. Only in the event that DOE were unable to demonstrate compliance

due to limitations in source term, flux and geochemistry would it be necessary for DOE to invoke dilution due to hydrodynamic dispersion as a mechanism necessary to meet the EPA Standard. Furthermore, for hydrodynamic dispersion to provide a useful mechanism for dilution in terms of the EPA Standard, it appears that the longitudinal dispersion would have to be in excess of 2 km. There is no testing mechanism of which TTI/NWC is aware that would provide a field measurement of longitudinal dispersion of that scale in basalts of the RRL in the time frame that is available to site characterization.

As TTI/NWC have written elsewhere (e.g., NWC Communication Nos. 21, 49, 52), for an information (data) need to exist, three conditions must be met:

1. The information must be needed in order to reach a decision.
2. The information must not already exist.
3. The information must be obtainable within the constraints of the program.

Hydrodynamic dispersion does not appear to meet the first test with respect to the overall EPA standard, and it is exceedingly unlikely that it would meet the third test, either, at least at a scale that is commensurate with performance assessment for the overall repository system. Thus, TTI concludes that there is no data need with respect to hydrodynamic dispersion as it applies to 40 CFR 191.13. As a consequence, TTI considers that the NRC Staff should not require a testing program aimed at defining hydrodynamic dispersion in the Hanford basalts as part of the information needed to determine compliance with 40 CFR 191.13.

6.2 HYDRODYNAMIC DISPERSION AND INDIVIDUAL PROTECTION REQUIREMENT

TTI and NWC emphasize that the analysis of this mini-report is aimed at the assessing compliance with the cumulative release standard of 40 CFR 191.13.

In NWC Communication No. 66, NWC raised to the NRC Staff a concern with respect to the Staff's position on demonstrating compliance with the individual protection requirement of 40 CFR 191.15. It is TTI's analysis that there are several transmissive units in the Pasco Basin that would meet the EPA tests as "significant sources of groundwater", and thus are subject to compliance assessment with respect to the individual protection requirements of 40 CFR 191.15.

In order to assess the dose limits of 40 CFR 191.15, it would appear likely that it will be necessary to be able to compute $C(x,t)$, which in turn would seem to imply that it will be necessary to have a reliable formulation of the advection-dispersion equation. If it were necessary to assess compliance against this standard, it would probably be necessary to define hydrodynamic dispersion in three dimensions, since it is possible to imagine circumstances under which the centroid of the radionuclide concentration would not impinge on the "significant source" but a laterally or vertically dispersed portion of the plume would so impinge. As was discussed in NWC Communication No. 66, there are very major computational difficulties associated with such compliance assessments, involving not only the flow and transport systems, but also the time-variant source term and the health-effects models.

TTI concurs with NWC that it would be well for the NRC Staff to consider the mechanics of developing a de minimus standard for compliance with the individual protection requirement that could be applied at all three sites. Based on this approach, TTI considers that the problem of meeting the individual protection requirement would become primarily a question of engineered barrier design, not geohydrology.

6.3 RECOMMENDATIONS

Based on the analysis of this mini-report, TTI has three principle recommendations:

1. Because compliance assessments for the overall EPA Standard do not appear to require a knowledge of hydrodynamic dispersion (at least within the range of longitudinal dispersivities that can be demonstrated in a feasible field test), TTI recommends that NRC Staff should not require testing of longitudinal dispersivity.

2. Since compliance assessments of the individual protection requirement would require a three-dimensional analysis of hydrodynamic dispersion at scales which cannot be tested (in excess of kilometers), TTI recommends that the NRC Staff develop a de minimus standard for releases of radionuclides during the first 1,000 years that will meet the need for a dispersion analysis that is irrelevant to the overall

standard by making the problem one of an appropriate engineered-barrier design.

3. TTI considers that further analyses of the sensitivity of the overall EPA Standard to hydrodynamic dispersion are not necessary. TTI recommends that if any further analyses with respect to hydrodynamic dispersion should be deemed necessary by the Staff (and the Staff rejects TTI's proposed de minimus approach), that additional analyses be directed at determining the relationships of source term, groundwater flux and velocity, and hydrodynamic dispersion that could be important to assessing compliance with the individual protection requirement.

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