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Complexity in the Validation of Ground-Water Travel Time in Fractured Flow and Transport Systems

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COMPLEXITY IN THE VALIDATION OF GROUND-WATER TRAVEL TIME IN FRACTURED FLOW AND TRANSPORT SYSTEMS

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ABSTRACT

Ground-water travel time is a widely used concept in site assessment for radioactive waste disposal. While ground-water travel time was originally conceived to provide a simple performance measure for evaluating repository sites, its definition in many flow and transport environments is ambiguous. The U.S. Department of Energy siting guidelines (10 CFR 960) define ground-water travel time as the time required for a unit volume of water to travel between two locations, calculated by dividing travel-path length by the quotient of average ground-water flux and effective porosity. Defining a meaningful effective porosity in a fractured porous material is a significant problem. Although the Waste Isolation Pilot Plant (WIPP) is not subject to specific requirements for ground-water travel time, travel times have been computed under a variety of model assumptions. Recently completed model analyses for WIPP illustrate the difficulties in applying a ground-water travel-time performance measure to flow and transport in fractured, fully saturated flow systems.

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INTRODUCTION

The objective of this paper is to provide a broad overview of the regulatory context of the ground-water travel-time concept and to illustrate the difficulties in applying this concept as a performance measure in fractured, fully saturated flow systems. The illustration of complexity and ambiguity in the ground-water travel-time concept comes from recent model analyses of potential contaminant transport along a major segment of the offsite travel path at the Waste Isolation Pilot Plant (WIPP) in the southwestern United States. The WIPP is a U.S. Department of Energy facility designed to provide a repository for emplacement of approximately 180,000 cubic meters of transuranic waste from defense-related activities [1].

REGULATORY CONTEXT OF THE GROUND-WATER TRAVEL-TIME CONCEPT

The ground-water travel-time concept has been formally and informally applied to a variety of potential radioactive waste disposal sites in the United States. In the United States, the generally applicable environmental standard governing geologic repositories for radioactive waste is specified by the Environmental Protection Agency (EPA) in 40 CFR 191 [2]. The EPA standard does not give a rule for ground-water travel time, but rather sets a limit for cumulative release of radioactive waste to the accessible environment (roughly speaking, at the land surface and crossing a boundary located 5 kilometers from the repository) over a 10,000 year period. The EPA standard, 40 CFR 191, has been remanded to the EPA for further consideration, and therefore, this paper discusses this standard as originally promulgated in 1985.

The Nuclear Regulatory Commission (NRC) is responsible for determining that repositories licensed for the disposal of high-level waste will meet the EPA standard. NRC has chosen to carry out this responsibility by writing a second rule, 10 CFR 60 [3], in such a way that compliance with this rule should assure compliance with 40 CFR 191. The NRC's implementation of the standard, 10 CFR 60, sets explicit rules about ground-water travel time. These rules state that a repository must be sited in such a way that the pre-waste-emplacement travel time of ground water along the fastest path of likely radionuclide travel from the projected location of the future repository's disturbed zone to the accessible environment is at least 1,000 years. However, the NRC rule does not specify how ground-water travel time is to be computed.

The Department of Energy is responsible for the siting and construction of radioactive waste repositories and has issued general guidelines for the siting process in 10 CFR 960 [4]. These guidelines define ground-water travel time as being calculated by dividing travel-path length by the quotient of average ground-water flux and effective porosity. The guidelines state that a site shall be disqualified if the pre-waste-emplacement ground-water travel time from the disturbed zone to the accessible environment is expected to be less than 1,000 years along any pathway of likely and significant radionuclide travel.

Most of the waste planned for disposal under the EPA standard, 40 CFR 191, is high-level waste comprising spent fuel from commercial power reactors; repositories for this waste must be licensed by the NRC. Repositories for the disposal of defense-generated transuranic wastes will not be licensed by NRC and such repositories must meet only the requirements of the EPA standard. Therefore, the WIPP is not subject to specific requirements for ground-water travel time. However, WIPP would clearly meet this aspect of the NRC regulation because the total travel path includes vertical flow through approximately 400 meters of undisturbed salt as well as lateral flow in a transmissive dolomite unit that overlies the salt.

FLOW AND TRANSPORT AT THE WIPP SITE UNDER BREACH CONDITIONS

Although WIPP is not subject to specific ground-water travel-time requirements, travel times have been computed under a variety of model assumptions [5,6,7,8,9] for characterizing flow and transport in the Culebra dolomite, which is a shallow, relatively transmissive unit considered the most likely pathway for offsite transport in the event of a repository breach. Recent model analyses for the WIPP illustrate significant difficulties in applying ground-water travel time as a performance measure in fractured, fully saturated flow systems. Difficulties in applying ground-water travel-time as a performance measure in fractured, unsaturated flow systems have been discussed by Kaplan et al., 1989 [10].

The calculations discussed in the remainder of this paper were carried out for the recently completed Supplement Environmental Impact Statement for the WIPP [1,8,9] and for sensitivity analyses of transport under breach conditions [6]. These calculations examine offsite contaminant transport in the Culebra dolomite as a result of a hypothetical penetration of the WIPP repository and an underlying pressurized brine source by a future hydrocarbon exploration well. The following discussion focuses on flow and transport in the Culebra dolomite segment of the total transport pathway.

Conceptual Model

The bedded salt formation containing the WIPP repository is underlain by isolated pockets of pressurized brine in fractured anhydrite units that have been mildly deformed in response to salt flow [8,11]. Recent geophysical measurements at WIPP indicate that pressurized brine may underlie a portion of the waste panels [8]. The human intrusion scenario considered for the Supplement Environmental Impact Statement [1,8,9] consisted of a hypothetical hydrocarbon exploration borehole penetrating a waste panel in the repository and an underlying pressurized brine pocket, thereby allowing release of contaminated brine into the Culebra dolomite (Figure 1).

The Culebra dolomite is an 8-meter-thick, fractured dolomite and is the most transmissive hydrogeologic unit overlying the WIPP repository. The Culebra has been the focus of extensive hydraulic testing at a variety of scales and of several conservative tracer tests [8]. Core analyses indicate that the average matrix porosity of the Culebra is 0.16 and tracer tests along the offsite transport pathway indicate an average fracture porosity of 0.0015 [6,8].

Numerical Implementation of Flow and Transport Models

Numerical simulations of the breach system depicted in Figure 1 have been implemented using the SWIFT II [12] flow and transport code. Three coupled model segments simulate fluid flow from a hypothetical pressurized brine pocket to the Culebra, ground-water flow in the Culebra, and contaminant transport in the Culebra to a boundary located approximately 5 kilometers from the repository. The first model segment is used to generate a fluid-loading and contaminant source term in the Culebra dolomite. In this segment, the pressurized brine pocket is dynamically linked to the Culebra dolomite through a breach borehole. Brine pocket properties are based on hydraulic testing of the brine pocket encountered in borehole WIPP-12, which is located approximately 2 kilometers north of the WIPP waste panels [8]. Brine flowing up the borehole is assumed to dissolve waste up to a specified solubility limit or until all mass for a given waste constituent is dissolved. Simulations were performed for a conservative solute and for four radioactive-decay chains (^{240}Pu, ^{239}Pu, ^{238}Pu, and ^{241}Am).

In the second model segment, ground-water flow in the Culebra is simulated using the model of LaVenue et al. [7], which has been calibrated using transmissivity information from 58 well locations, head information from 61 observations wells, and transient stresses from three large scale pumping tests and from shaft construction. A portion of the undisturbed flow field from the LaVenue et al. model is presented in Figure 2. Two-dimensional transport simulations utilized the undisturbed flow field because the injection of brine from the breach borehole had a negligible effect on the average ground-water flux along the offsite travel path.

In the third model segment, contaminant transport along the fastest offsite travel path in the Culebra (Figure 2) is simulated for two-dimensional, single- or dual-porosity conditions. Dual-porosity transport parameters have been derived from convergent-flow tracer tests at two hydropad locations along the principal offsite transport pathway [6,8]. The contaminant source in the Culebra has been specified as a variable-width strip-source, which is computed assuming an idealized plume from point-source injection rates calculated using the first model segment.

Travel Time Implications of Model Results

This discussion focuses only on travel time in the Culebra dolomite from the breach borehole to a boundary located approximately 5 kilometers from a vertical projection of the waste panels. The location, length, and average flux for the fastest travel path in the Culebra have been determined using a particle tracking code. For the LaVenue et al. flow model [7], the fastest travel path originates above the southwest waste panel, follows flow east-southeastward toward a higher transmissivity zone, and then continues southward along that zone (Figure 2). The length of this travel path is approximately 6000 meters and the average ground-water flux is approximately 1.9×10^{-9} m/s. The next step is to divide the quotient of path length and average flux by effective porosity. However, in a fractured porous medium, the concept of effective porosity is ambiguous. Assuming that all flow occurs through the fractures, with a porosity of 0.0015, yields a ground-water travel time of approximately 150 years. Assuming that no preferential flow occurs in the fractures and that water moves uniformly through a combined medium having a fracture-plus-matrix porosity of 0.1615 yields a ground-water travel time of approximately 16,000 years. Which, if either, of these two travel times should be taken as the performance measure? The fracture-only travel time may be unrealistically short because it assumes that the matrix plays no role in contaminant migration. The fracture-plus-matrix travel time may be unrealistically long because it assumes that the matrix participates fully during transport and contaminant migration is not at all enhanced by the presence of fractures. The two-orders-of-magnitude difference between these travel times illustrates that a flow-based travel time yields significant ambiguity when used as a performance measure.

From both technical and regulatory standpoints, the critical issue is contaminant transport, not ground-water flow. In a fractured porous medium, contaminant-transport time is strongly influenced by the physical properties of the fractures and rock matrix, and by the free-water diffusivity of a given contaminant (in addition to retardation due to chemical interactions and decay of radioactive contaminants). These physical properties control the degree of interaction between fractures and matrix, and therefore, strongly influence offsite contaminant-transport times and rates.

Simulations of the transport of a conservative, nonretarded contaminant in the Culebra dolomite provide an example of the additional information that transport simulation provides. These simulations assume a constant contaminant concentration at the breach well of 2.4×10^{-7} kg/kg and a source-plume width that decreases with time as the driving pressure depletes in the underlying brine pocket. Breakthrough curves at the 5-kilometer boundary are presented for single-porosity, fracture-only transport; single-porosity, fracture-plus-matrix transport; and dual-porosity transport, with transport interaction (matrix diffusion) between fractures and matrix (Figure 3). Single-porosity, fracture-only transport yields a peak concentration of 6×10^{-9} kg/kg at approximately 200 years, which is of the same order as the fracture-only ground-water travel time. Single-porosity, fracture-plus-matrix transport yields a peak concentration of 4×10^{-9} kg/kg at approximately 22,000 years, which is of the same order as the fracture-plus-matrix ground-water travel time.

Actual contaminant breakthrough at the 5-kilometer boundary would be expected to fall some time between these two extremes, and when it will occur depends on the degree of transport interaction between fracture and matrix. Only a dual-porosity simulation provides the critical information needed to determine when contaminant breakthrough will occur. The dual-porosity simulation results (Figure 3) suggest that for the estimated Culebra transport properties, there is a significant degree of interaction between fractures and matrix. For the dual-porosity simulation, the peak concentration of 3×10^{-9} kg/kg occurs at approximately 24,000 years, which is similar to the fracture-plus-matrix peak concentration and breakthrough time. However, the influence of the fractures can be seen in the earlier breakthrough times at lower concentration levels. For example, breakthrough at the 10^{-16} kg/kg concentration level occurs at approximately 5000 years in the fracture-plus-matrix simulation, but at only approximately 2000 years under dual-porosity conditions (Figure 3). Another way to view the difference is to note that at approximately 5500 years, the single-porosity, fracture-plus-matrix and dual-porosity simulations differ in contaminant concentration at the 5-kilometer boundary by approximately four orders of magnitude (Figure 4).

CONCLUSIONS

Ground-water travel time is intended to provide a simple, effective performance measure for characterizing hydrogeologic containment at a potential radioactive waste disposal site. The calculations presented in this paper, which are based on actual site-characterization data from a repository that is currently under development, illustrate that ground-water travel time is an highly ambiguous performance measure and does not provide a meaningful surrogate for characterizing contaminant transport behavior in fractured, fully saturated flow systems. As an alternative, a performance measure based on *transport rather than flow* would provide a more meaningful measure for assessing site suitability for radioactive waste disposal. The discussion presented in this paper focuses only on issues surrounding the physical definition of a performance measure and does not consider issues associated with the characterization of uncertainty, which is also an important component of the total performance assessment.

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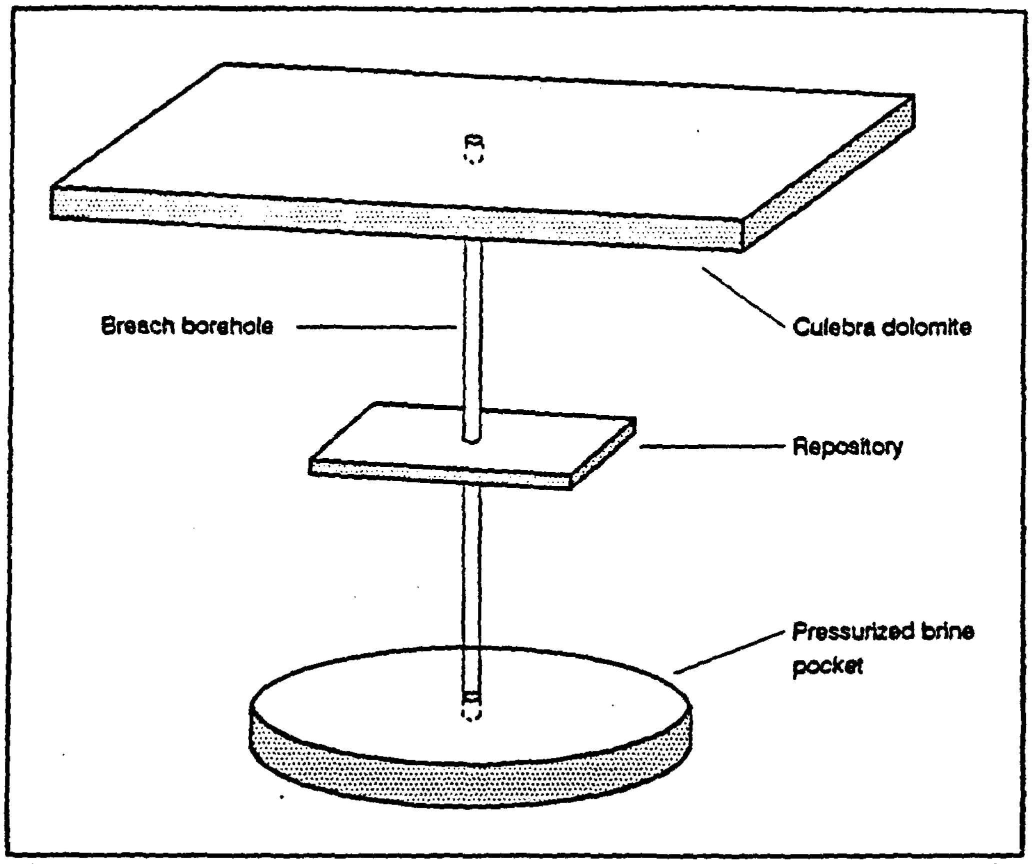

Figure 1. Schematic diagram of flow system considered for breach simulation. This system consists of a borehole penetrating both the repository and an underlying pressurized brine pocket, with contaminant release and offsite transport in the Culebra dolomite.

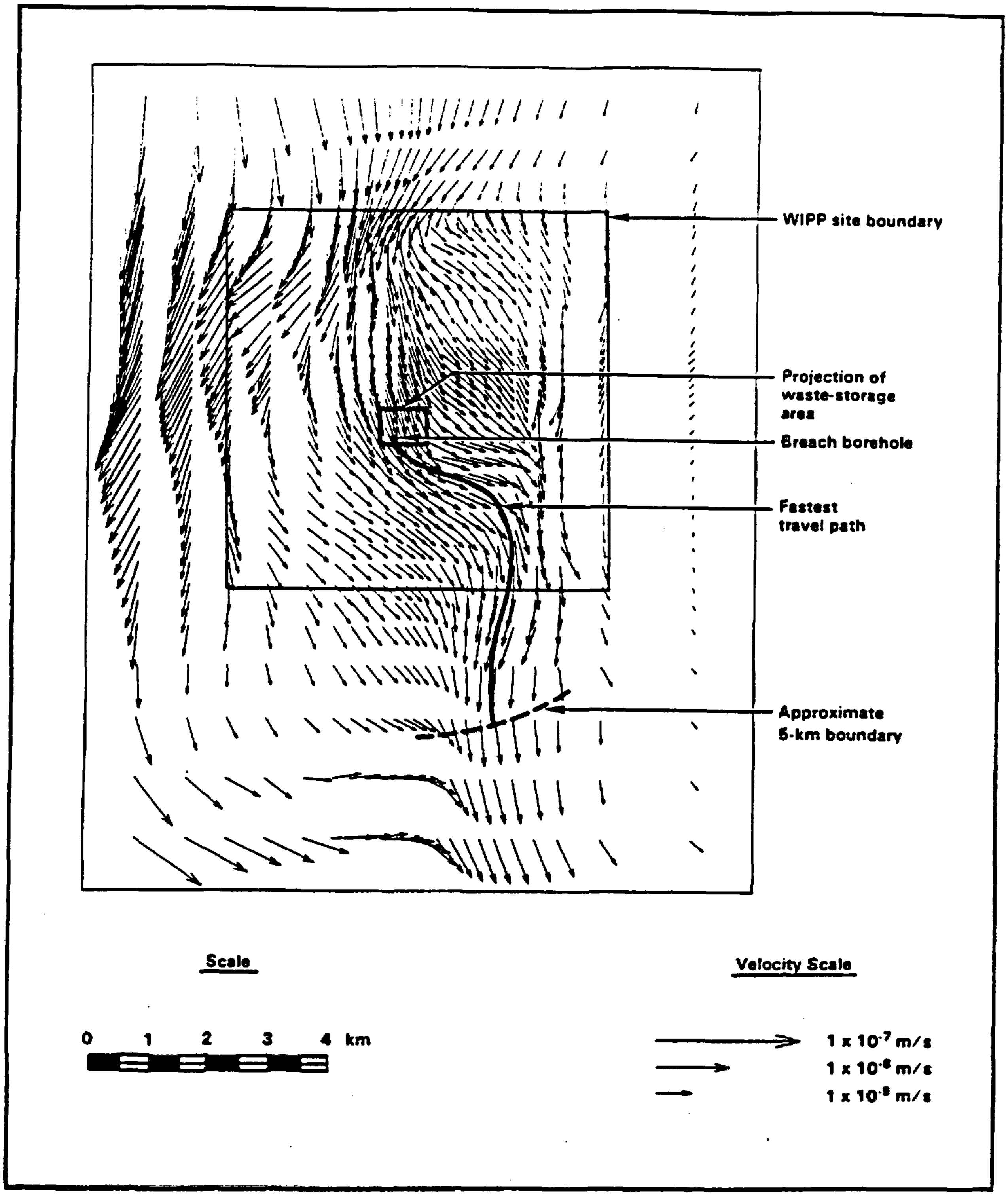

Figure 2. Simulated flow field (Darcy velocities) for the Culebra dolomite under undisturbed conditions [7]. Fastest transport pathway from a breach borehole to the approximate 5-kilometer boundary is also shown.

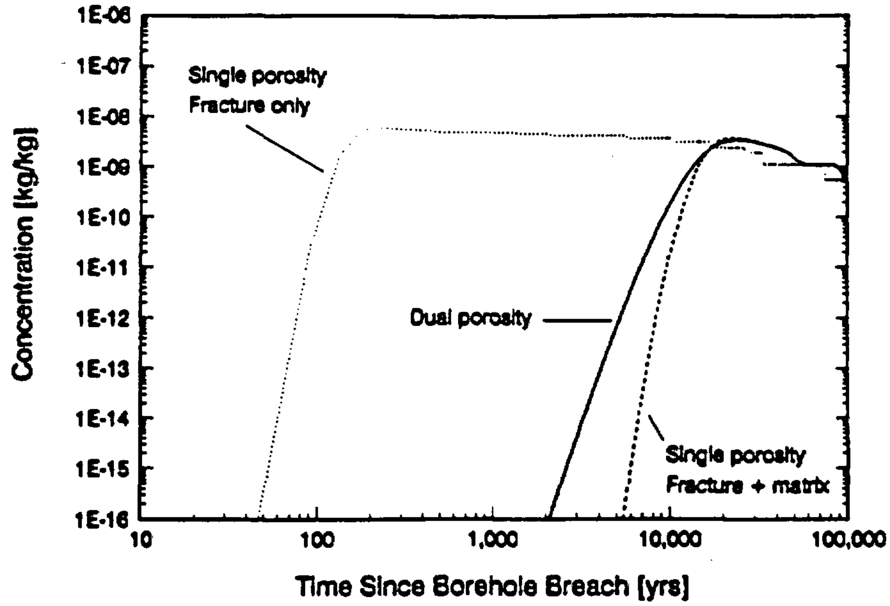

Figure 3. **Contaminant concentration versus time at the 5-kilometer boundary for a conservative, nonretarded solute. Curves depict single-porosity, fracture-only transport; single-porosity, fracture-plus-matrix transport; and dual-porosity transport.**

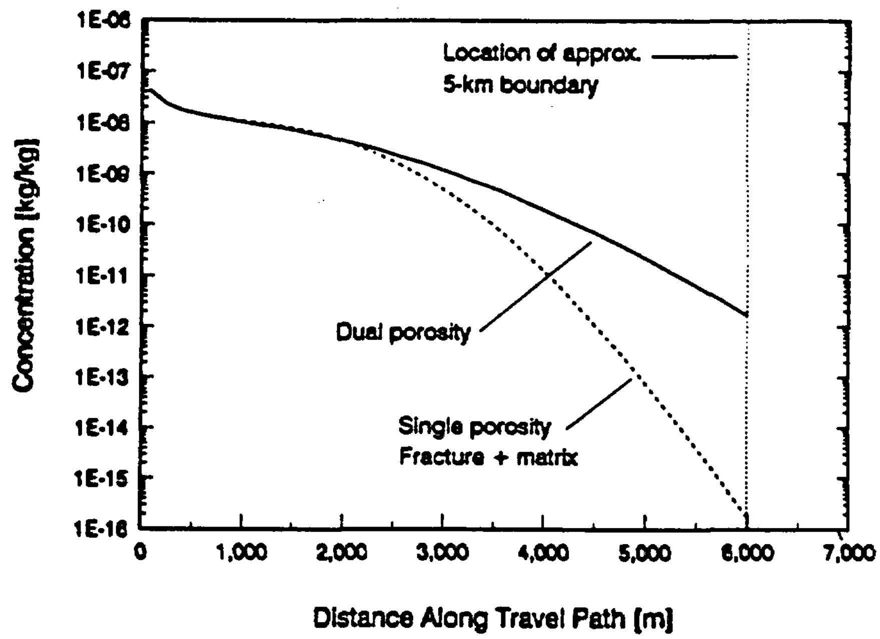

Figure 4. Contaminant concentration profiles along the transport pathway at approximately 5500 years. Curves depict single-porosity, fracture-plus-matrix transport and dual-porosity transport.