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Saturated Zone Plumes in Volcanic Rock: Implications for Yucca Mountain

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ABSTRACT- This paper presents a literature survey of the occurrences of radionuclide plumes in saturated, fractured rocks. Three sites, Idaho National laboratory, Hanford, and Oak Ridge are discussed in detail. Results of a modeling study are also presented showing that the length to width ratio of a plume starting within the repository footprint at the Yucca Mountain Project site, decreases from about 20:1 for the base case to about 4:1 for a higher value of transverse dispersivity, indicating enhanced lateral spreading of the plume. Due to the definition of regulatory requirements, this lateral spreading does not directly impact breakthrough curves at the 18 km compliance boundary, however it increases the potential that a plume will encounter reducing conditions, thus significantly retarding the transport of sorbing radionuclides.

MOTIVATION

At the Yucca Mountain Project (YMP) site, the natural system is the final transport barrier preventing waste from reaching the accessible environment. To understand the role played by the natural system in making the safety case for Yucca Mountain, one must first set the regulatory context. For the nominal case (excluding the impact of volcanism), the exposure scenario being studied is one in which a supply well located downstream of the repository produces water containing radionuclides that have escaped the engineered barrier and traveled to the 18 km compliance boundary. This is a conservative approach to avoid basing regulations on uncertain future use scenarios. Within this regulatory context, certain details about the transport system become of primary importance, and others become unimportant. To illustrate this, consider a radionuclide that is released at a time-varying rate $\dot{m}_s(t)$ from the source, and travels through the natural system. The mass flux (mass per unit time) at the compliance boundary $\dot{m}_{cb}(t)$ can be expressed as a simple convolution over all possible travel times, corrected by radioactive decay of a given species. Time zero is considered to be the time of emplacement and radionuclide mass flux predictions are required from this point to the regulatory time of interest: 10,000 years for the original standard, and a time exceeding the time of peak dose for the draft peak dose standard.

Besides radioactive decay, the only processes in the natural system leading to lower fluxes at the compliance boundary are those that sequester radionuclides in the natural system by affecting the travel time through the combined unsaturated zone-saturated zone (UZ-SZ) system. For radionuclides with half-lives that are short compared to the regulatory time period of interest, the relevant time frame is the half-life; the natural system is effective if travel times exceeding $t_{1/2}$ dominate the system. For very long-lived radionuclides, the regulatory time frame becomes the controlling factor; radioactive decay has a minimal impact on reducing the mass flux, and only processes that extend the travel time distribution to values greater than the regulatory time frame are important. It should be noted that, even if travel times are too short to provide complete isolation, the natural system smoothes out any sharp, high-concentration pulses of radionuclides that might be released, providing a limit to the degree to which such pulses can be transmitted to the compliance boundary.

The processes of advection, diffusion into dead-end pore space, sorption onto rock surfaces and colloid facilitated transport are expected to significantly affect the RTD, and thus have a first-order effect on SZ performance. The other processes of potential significance are longitudinal and transverse dispersion. Longitudinal dispersion (dispersion in the direction of fluid flow) spreads radionuclides in space, and therefore acts to broaden the distribution of arrival times at a location along the flow path. However, in comparison to other processes that push the entire RTD to longer or shorter travel times, longitudinal dispersion has a small to moderate effect on SZ performance Transverse dispersion is the process by which local heterogeneities cause pathways spread in a direction normal to the main flow direction. In contaminant transport studies transverse dispersion is known to have a significant impact on the local concentration within a plume However, because the mass flux at the 18 km compliance boundary is the relevant metric for determining the impact of the natural system on dose, transverse dispersion is expected to have a small effect on SZ performance. An exception to this could arise if the lateral spreading of the plume causes the radionuclides to enter portions of the aquifer with more strongly retarding conditions. If this were to occur, transverse dispersion coupled with retarding conditions could have a first order effect on the travel time on a portion of the plume.

The expected flow paths for the radionuclide transport through the SZ at Yucca Mountain start in fractured volcanic units near the repository footprint and transition into alluvium further downstream. The focus of this study is the influence of dispersion within the saturated volcanic units on the breakthrough curves (BTCs) at the compliance boundary as well as the effect of dispersion on plume shapes.

IMPACT OF HIGHER TRANSVERSE DISPERSIVITY VALUES ON SZ TRANSPORT MODEL

The current Site-Scale SZ Transport model [1] was used to assess the impact of higher values of transverse dispersivities in the volcanic units on transport pathways and the breakthrough curves obtained at the 18 km compliance boundary. The breakthrough curves obtained for a high value of horizontal transverse dispersivity in volcanics (10 m, taken equal to the base case value of longitudinal dispersivity) compared to the 0.05 m for base case, and for a high value of vertical transverse dispersivity (10 m compared to the 0.0005 m for base case) are shown in Figure 1 along with the breakthrough curve for the base case Site Scale SZ Transport model. As expected, the breakthrough curves are not very sensitive to the values of the transverse dispersivities in the volcanics, and the time for breakthrough of 50% of the inlet mass is almost unchanged. This is due to the fact that the breakthrough curves include the entire mass crossing the boundary that stretches along the entire model domain in a direction approximately normal to flow. The somewhat earlier breakthrough seen for the case of high vertical transverse dispersivity is due to some solute dispersing into a region of higher flow velocities.

The path lines for nine particles for a distributed source with initial locations spread out over the repository footprint are shown in Figure 2. Those for a high value of vertical transverse dispersivity (10 m) are in red, along with the path lines with the same starting locations for the base case shown in black. The plumes remain relatively narrow, largely due to the converging nature of the flow field.

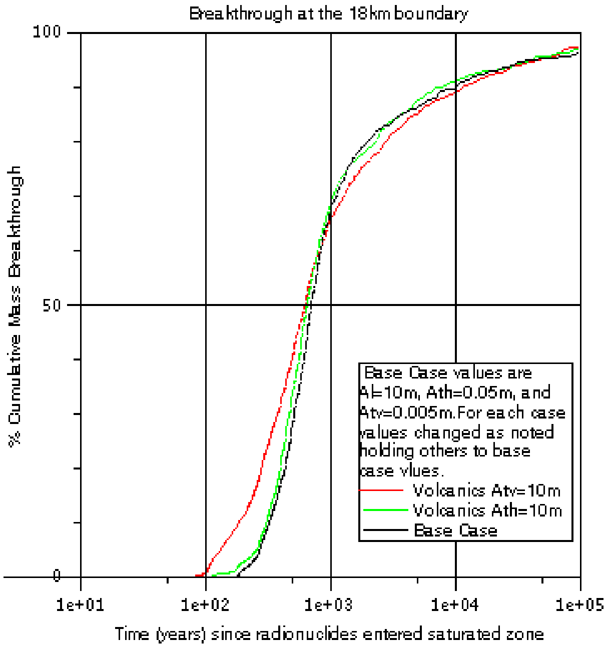


Figure 1: BTC for high values of transverse dispersivities compared with the base case results.

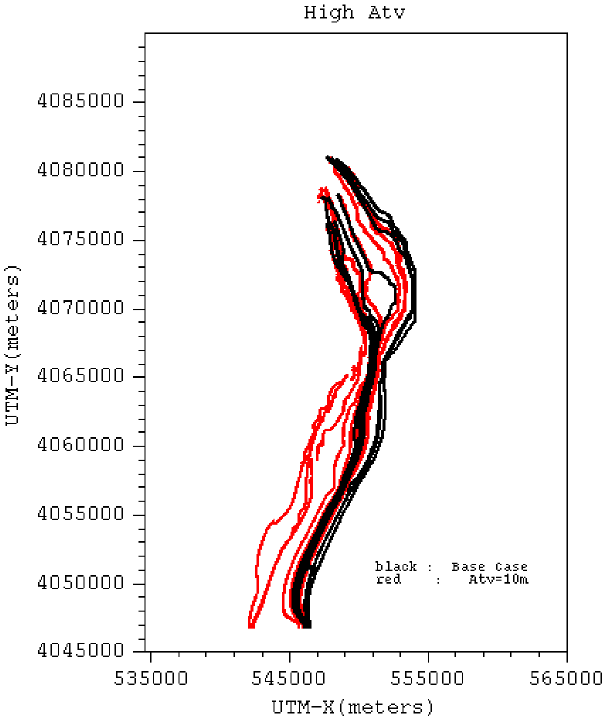


Figure 2: Particle travel paths indicating plume shapes resulting from a distributed source for the case of high vertical transverse dispersivity compared to the base case

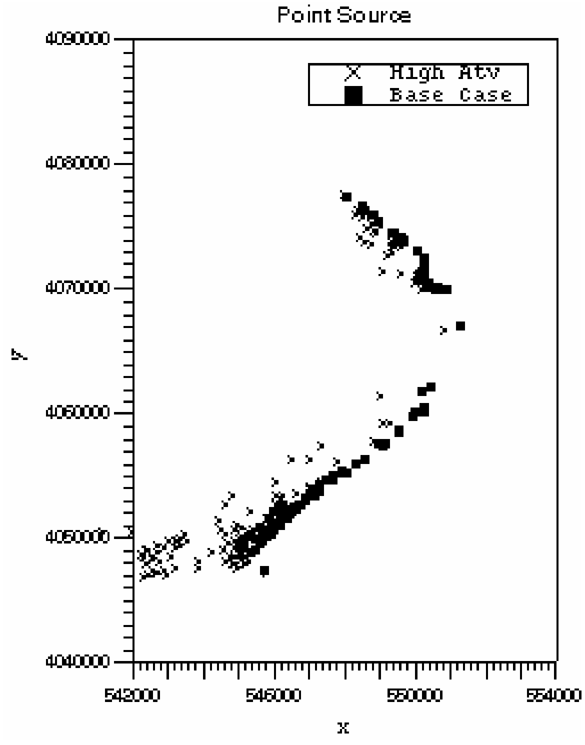


Figure 3: Plume Shapes after 1000 years for a Point Source, Base Case and High Vertical Transverse Dispersivity

Figure 3 shows the plumes resulting from a point source located near the middle of the repository footprint for the base case compared with that for the case of high transverse dispersivity. There is significant longitudinal spreading of the plume, with a long tail resulting from the matrix diffusion effects in the volcanics. The length to width (L/W) for the leading portion of the plume decreases from a value of about 20:1 for the base case to about 4:1 for the high transverse dispersivity case. Thus, although the plume remains relatively narrow, transverse dispersion does make it wider.

A major factor contributing to the narrowness of the predicted solute plume is the converging nature of the flow field near the southern end of the base case flow model. The base case flow model [2] has a significant flux entering the model in the southern third of the eastern boundary and exiting through the eastern third of the southern boundary. This restricts any plume spreading to the east. The transmissivity distribution in the calibrated flow model with the base case hydrogeologic framework model (HFM) restricts any spreading of the plume to the west. This creates a narrow flow zone, thus leading to a narrow plume near the southern model boundary repository (Figure 2). Future refinements of the HFM and the flow model could significantly impact the results presented in this section regarding the breakthrough curves and the plume shapes. Although the impact of higher transverse dispersivity values on the BTC is minimal, a wider plume could potentially result in a higher percentage of the radionuclides encountering zones of enhanced retardation, such as zones of reducing conditions, thus resulting in increased transport times.

LITERATURE SEARCH

Literally thousands of scientific papers, technical reports, proceedings papers, and abstracts exist that document contaminant transport studies. This study was mainly limited to reviewing work conducted at field sites with fractured-rock aquifers and radioactive contaminants or tracers. Search methods included searches through library search engines such as GEOREF, LANL, DOE, and Science Server, or via Internet search engines. Key words for these searches included “dispersivity”, “fractured rocks”, “radioactive plumes”, “contaminant plumes”, or “field-scale contaminant transport”, as well as known site names. Web pages for known research sites, such as Hanford or Mirror Lake, or for research agencies such as the U.S. Geological Survey or the National Laboratories were visited and searched. When possible, personal contacts with researchers were made to seek out additional information. Relevant references, cited in research papers being reviewed, were obtained when possible.

The sites considered in this survey that had reported plume and dispersivity data in fractured rocks are INL (USA), Hanford (USA), and Oak Ridge (USA). These sites are described in more detail later in this paper. The following sites in sedimentary formations were also considered for comparison: Cape Code (USA), Condi Aquifer (USA), Amargosa Tracer Site (USA), SE Wisconsin Dolomite (USA), Paducah (USA), Norton (USA), and Whidbey Island (USA). Sites included in the literature survey that had no reported plume data but did report tracer tests or dispersivity values are Kamaishi (Japan), El Berrocal (Spain), Stripa (Sweden), Grimsel (Switzerland), NTS (USA), LANL(USA), YMP (USA), Creston (USA), Oracle(USA), Chalk River (USA), Mirror Lake (USA), NWAC(USA). These sites are not considered further in this paper. Sites included in the literature survey that had no reported data on saturated zone ground water plumes or tracer tests are Olkiluoto (Finland), Palmottu (Finland), Mizunami (Japan), Aspo (Sweden), Pinawa (Canada), Sellafield (UK), Konrad (Germany), Fanay-Augeres (France), Mayak (Russia), Tomsk (Russia), Beishan (China), and Kalpakkam (India). These sites are not considered further in this paper.

DISCUSSION OF PREVIOUS DISPERSIVITY REVIEWS

Two important reviews of dispersivity have been written by Gelhar et al. (1992)[3] and Schulze-Makuch (2005) [4]. Additionally, Walton (1984, table 2.6)[5] presents summary data for both longitudinal and transverse dispersivity.

Gelhar et al. (1992)[3] conducted a review of 106 dispersivity values from 59 field sites. They classified the dispersivity values into three reliability classes: high reliability values accurate within a factor of 2, low reliability values accurate than within 1-2 orders of magnitude, and intermediate reliability values between the two extremes. Of these sites, 21 were consolidated-rock sites. Site scales ranged from 1.2 to 50,000 m, longitudinal dispersivity values ranged from 0.2 to 910 m, and transverse dispersivity values ranged from 8 to 1,370 m. Most of the dispersivity values were considered to be of low reliability and only one value was considered to be of high reliability. None of the consolidate-rock sites were in volcanic tuffs, although several sites were in basalt. The largest longitudinal and horizontal transverse dispersivity values (910 and 1370 m, respectively) were obtained from a site in Idaho underlain by basalt [3].

A more recent review of dispersivity values by Shulze-Makuch [4] compiles longitudinal dispersivity data from 109 studies. This review [4] categorizes the dispersivity values with the same reliability categories used in the Gelhar et al. (1992) review [3]. For 20 consolidated-rock sites with test scales of greater than 1 m, longitudinal dispersivity values ranged from 0.003 to 76 m. The largest dispersivity value (76 m) was obtained from a site in Hawaii underlain by basalt.

RESULTS FOR SELECTED SITES

Three sites with documented wide plumes in fractured rock formations were identified for further considerations : the Snake River-INL, Oak Ridge, and Hanford. All of these sites are within the USA.

The Snake River Plain Aquifer at the Idaho National Laboratory

Site Description: Idaho National Laboratory (INL) overlies the Snake River Plain aquifer in southeast Idaho. The aquifer consists of thin, lobate flows of Tertiary and Quaternary basalt interlayered with smaller volumes of sedimentary material at irregular intervals. Basalt flow interiors are fine-grained and typically massive. In contrast, the margins of the flows are commonly highly fractured and rubbly, providing conductive flow paths [6]. The aquifer is unconfined and groundwater flow is fracture-dominated.

The INL has served as the United State’s primary facility dedicated to the development of atomic energy since 1951. Until the mid 1980s contaminated liquid waste was disposed of through direct injection to the aquifer and via percolation ponds. The majority of the liquid waste discharged to the aquifer was released at the Test Reactor Area (TRA) and the Idaho Nuclear Technology and Engineering Center (INTEC). In addition, contaminants are present in the aquifer due to waste disposal from the

Radioactive Waste Management Complex (RWMC), Test Area North (TAN), and the Central Facilities Area (CFA). Contaminant plumes extend down gradient from many of these sites and some contaminants can be tracked to near the southern boundary of the INL.

Results: One of the plumes reported for the INL site is a broad tritium plume [6] in the INTEC/TRA region as shown in Figure 4. The lobate shape of the plume, with a L/W ratio of roughly 1.5:1, suggests that transverse dispersion in significant. This observation is supported a modeling study [7], which mentions a "remarkable degree of lateral dispersion" that dilutes and spreads the waste quickly. A 2-D model is presented [7] with a longitudinal dispersivity of 91 m and a transverse dispersivity of 137 m. These dispersivity estimates are ranked as being of low reliability by Gelhar et al. (1992) [3], probably due to the 2-D nature of the model and the somewhat uncertain definition of the source term that is intrinsic to modeling studies based on contaminant plumes.

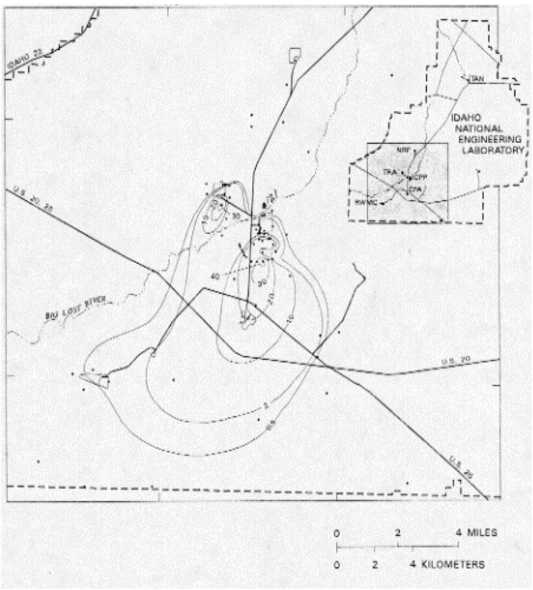


Figure 4: Distribution of tritium in water from the Snake River Plain aquifer, October 1991. Contours are lines of equal tritium concentration in pCi/mL [8].

Technetium-99 is another anthropogenic contaminant that was injected into the aquifer at INTEC. The plume had [9] roughly the same size and shape as the tritium plume shown in Figure 4.

At the INL Test Area North (TAN) site a plume that consists of volatile organic compounds and radionuclides originated from direct injection into the aquifer. In contrast to the INTEC plume, this plume is more elongate, with length to width ratios of roughly 2.5 to 3.

Oak Ridge

Site Description: The Oak Ridge Reservation in east Tennessee is the site of three major DOE facilities – Oak Ridge National Laboratory, the Y-12 Plant, and the K-25 Gaseous Diffusion Plant. All of these sites have generated radioactive and other wastes that were disposed of in shallow burial grounds in different parts of the Reservation. The underlying geology mainly consists of alternating limestone and shale units that are overlain by weathered regolith of varying thickness. The rocks are often steeply dipping and are oriented along a regional northeast-southwest strike. There are several regional thrust faults and many smaller-scale faults and folds. Most of the ground-water flow occurs in the weathered regolith, although a portion of the flow is deeper, within the fractured bedrock units [10]. Ground-water flow directions are somewhat structurally controlled, and are often characterized as being "along strike"; however, flow is also controlled by the presence of streams that influence short, local flow paths [11].

The two studies considered for this paper were conducted in two different valleys on the Reservation. The tracer tests discussed in [12] were conducted in Melton Valley. Melton Valley is underlain by alternating shale and limestone units of the Conasauga Group, which is in turn overlain by regolith [11]. The regional strike is N 56^{o}E, and dip of beds is to the southeast generally at angles ranging from 10^o to 20^o. Another tracer test was conducted in Bear Creek Valley [13], which is also underlain by rocks of the Conasauga Group. Ground water generally occurs under unconfined conditions within the regolith and upper part of the bedrock units, although it circulates more deeply into the bedrock units in Bear Creek Valley than in Melton Valley [10]. Most ground-water flow is towards nearby streams in both valleys. The hydraulic conductivity of the bedrock units has been characterized as having a strong anisotropy parallel to strike, based on aquifer test analyses [13].

Results: Two plumes in Melton Valley developed as a result of tracer tests using tritium [14]. Flow occurs in the weathered bedrock zone. The scale of these tests ranged from about 3 to 6 meters. The development of the plumes (Figure 5) over a period of nearly 1,800 days shows that, although they initially had a somewhat elongated shape normal to strike, the plumes exhibited large transverse spreading parallel to strike over time. The length to width ratio of the plume changed from about 1.2 to 1.8 to about 0.8 to 1.1 over time. It is likely that the plume spreading occurs due to the hydraulic gradient being at an angle to the fracture orientations.

Lee et al. (1992) [13] conducted a tracer test using rhodamine dye in Bear Creek Valley. The scale of that test was about 45 meters and the plume had an elongated shape oriented approximately parallel to strike. The length to width ratio of the plume ranged from about 7.5 to 9.1. Longitudinal dispersivity was reported as 1.0 meter, and transverse dispersivity was reported as 0.1 meters, on the basis of model analysis [13].

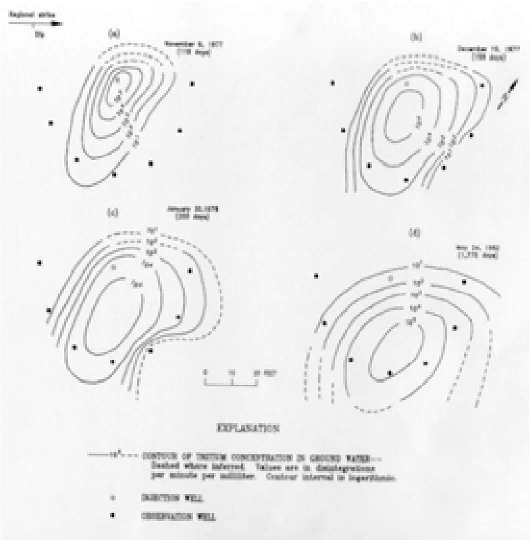


Figure 5: Tritium concentrations at a low-level radioactive-waste burial ground near Oak Ridge, Tennessee, at (a) 118 days, (b) 158 days, (c) 200 days, and (d) 1,775 days after tracer injection (Webster, 1996, fig. 14) [12].

Stafford et al. (1998) [15] examined the influence of fracture geometry on dispersion, citing the two Oak Ridge tracer studies as examples, through the use of model analysis. They concluded that the different shapes of the plumes may be influenced by the relative length and orientation of the fractures. The large transverse spreading of the plumes in Melton Valley could generally be replicated through the use of a few truncated fractures along with porous media flow (Stafford et al., 1998, p. 98) [15]. They attribute the long, narrow plume in Bear Creek Valley to long fractures that are oriented parallel to the hydraulic gradient.

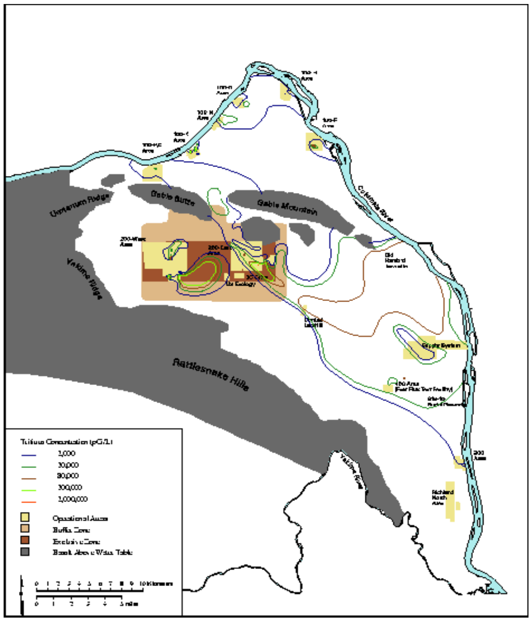
Hanford

Site Description: The U.S. Department of Energy's Hanford site is located in south-central Washington and is a plutonium production complex with nine nuclear reactors. The Hanford site is undertaking the world's largest environmental cleanup project with millions of liters of liquid waste and thousands of metric tons of solid nuclear materials. The site contains about a trillion liters of ground water that has various contaminants in concentrations above drinking water standards, spread out over 208 square kilometers [16]. The site was once under consideration as a potential high-level radioactive-waste repository (Basalt Waste Isolation Project).

The site is underlain by a sequence of basalt flows of the Columbia River Basalt Group, a series of flood basalts that occupy more than 160,000 km^2 [17] of the Pasco structural basin. These flows have been characterized as having high-permeability flow tops and interbeds separated by lower-permeability, dense interiors [18]. The basalts are overlain by 0 to greater than 60 m of fluvial and lacustrine sediments of the Ringold Formation and the glacio-fluvial Hanford Formation [17]. Ground water generally occurs under unconfined conditions in the unconsolidated sediments and both unconfined and confined conditions in the basalts. Depths to water range from less than 0.3 m near the Columbia River to more than 100 m. Ground-water flow generally is horizontal within the flow tops and interbed zones and vertical through the denser parts of the basalt flows where vertical fractures are present [19]. Ground water in the unconfined part of the ground-water system generally flows from recharge areas in the west toward the Columbia River to the north and east [17]. Within the deeper basalts, ground-water flow appears to be to the southeast [18].

Results: Lavenue and Domenico (1986) [18] discuss regional dispersivity values for the Hanford site and show an extensive chloride plume of presumed natural origin within several basalt formations. The chloride plume extends over a distance of more than 35 km, and is oriented southeast along the presumed ground-water flow direction within the basalts [18]. The plume is relatively wide with a length-to-width ratio of approximately 2.0. Reported dispersivity values range from 20 to 600 m; with values between 40 and 60 m being most likely [18].

Cole et al. (1998) [17] discusses plumes in unconsolidated sediments that overlie the basalts for tritium (for 1979 and 1996) (Figure 6), iodine-129, technetium-99, strontium-90, and uranium. The shapes of the plumes range from nearly circular to somewhat elongated, and the length-to-width ratios of the plumes ranges from about 1.0 to about 4.3. A longitudinal dispersivity value of 90 m, and a transverse dispersivity value of 9.0 m were used in the model.



Observed Tritium Plume for 1996 Conditions

Figure 6: Tritium plumes at the Hanford site in 1966 [17].

CONCLUSIONS

Contaminant plumes reviewed during this study occur in a wide variety of shapes, ranging from long and narrow to nearly circular. Within fractured-rock aquifers the shape of the plume appears to be influenced by the length and orientation of major fractures in relation to the hydraulic gradient or by other structural or lithologic controls on the ground-water flow path. The long and relatively narrow plume predicted by the Yucca Mountain saturated-zone transport model [2] is, therefore, not necessarily anomalous.

The effects of higher transverse dispersivity values on the BTCs at YMP as predicted by the SZ transport model are very minor. The narrow shape of the plume is largely governed by the converging nature of the flow field, although assigning higher transverse dispersivity values for transport through the saturated volcanics results in a slightly lower length-to-width ratio. The converging flow field could be altered by future changes to the base case flow and hydrogeologic framework models. There is a potential for transverse dispersivities to have a significant impact on the BTCs if the lateral spreading of the plume causes the radionuclides to enter portions of the aquifer with more strongly retarding conditions.

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