RAI Volume 3, Chapter 2.2.1.4.2, First Set, Number 2, Supplemental Question:

> The DOE response indicates that, despite the very short travel time in the borehole, the relatively slow matrix diffusion process has a significant impact (e.g., non-sorbing species increase in travel time to 1,250 yrs. and a moderately sorbing species increase to 64,000 yrs.). Although the DOE has provided information to support the increases in travel time, travel times of this length appear to be inconsistent with the travel times estimated for fractures in the UZ (e.g., the SAR figures 2.3.8-50 and 51). If the borehole travel times are estimated based on the host rock properties (fracture and matrix), clarify the basis for such different travel times associated with transport in the fractures of the host rock vs. the assumed fractures in the borehole.

1. RESPONSE

The stylized human intrusion borehole travel times are not expected to be identical to the travel times through fractures in the unsaturated zone transport submodel, which is designed to simulate radionuclide transport through a network of fractures subject to flow along preferential pathways and flow diversion to faults (SAR Sections 2.3.2.2.2.1 and 2.3.8.4.1). The concept of preferential flow is simulated in the unsaturated zone flow and transport models using the Active Fracture Model (AFM) proposed by Liu et al. (1998) and discussed in Section 1.2. The conceptual model for the stylized borehole (e.g., a single continuous fracture subject to matrix diffusion into surrounding rock) uses only a subset of the unsaturated zone rock properties comprising the properties of fractures and rock matrix for the rock types within the repository horizon. Note that the AFM was developed for fracture networks rather than a single fracture, consequently, the AFM model does not apply to the conceptual model for the human intrusion borehole pathway (SNL 2007, p. 7-51). The conceptual model differences between a stylized intrusion borehole and the undisturbed unsaturated zone component of the Lower Natural Barrier account for the differences in travel times associated with radionuclide transport through the unsaturated zone. An analysis of the results in mean radionuclide travel times through the stylized human intrusion borehole show that they fall within the upper ranges of transport times associated with transport through the unsaturated zone model.

1.1 HUMAN INTRUSION BOREHOLE

The conceptual model for the stylized analysis of an inadvertent human intrusion includes the transport of radionuclides released from a single intruded waste package vertically downward through the intrusion borehole as defined in 10 CFR 63.322. The borehole extends 190 m from the bottom of the waste package, through the unsaturated zone, to the saturated zone. The borehole is conceptualized to be an uncased, degraded borehole that is modeled as a single continuous fracture subject to matrix diffusion into surrounding rock using matrix and fracture properties of the unsaturated zone rock types comprising the repository horizon. The rubble fill in the borehole is considered to have homogenous properties similar to the undisturbed repository host rock matrix, while any preferential pathways within the rubble fill are given fracture properties of the repository host rock. The collapsed matrix blocks are expected to occupy about 99% of the borehole volume, while about 1% of the borehole volume is occupied by a continuous fracture pathway (SNL 2008a, Section 6.7.3.2). The percent of total volume attributed to fracture and matrix represents a simplified estimate of the effective fracture porosity in the borehole. The lower the effective fracture porosity the faster the flow velocities in the fracture. A dual-porosity approach is adopted by modeling a discrete fracture that is surrounded by the rock matrix. Transport through the borehole is modeled using the GoldSim pipe pathway element configured as two parallel plates fully surrounded by a porous medium. Fracture flow occurs vertically between the walls of the fracture. The rate of volumetric water flow in the borehole is the product of the percolation flux (mm/yr) at the base of the Paintbrush Tuff nonwelded (PTn) unit and the borehole cross-sectional area. However, unlike the unsaturated zone model, which simulates a fracture network subject to transport along preferential pathways or active fractures, the stylized borehole is conceptualized as a continuous fracture pathway without any linings or infill and as such has a large effective surface area for communication between the fracture and the matrix in the degraded borehole and along the borehole perimeter. The matrix in the degraded borehole and along the borehole perimeter has the properties of undisturbed unsaturated zone matrix comprising the repository horizon. The resulting fracture–matrix interaction retards the rate of transport of radionuclides from the repository horizon to the saturated zone (as detailed in the original response to RAI 3.2.2.1.4.2-002) to a greater extent than in the unsaturated zone model. The sampled uncertainties that affect transport in the unsaturated zone borehole include fracture saturation, matrix saturation, matrix partition coefficients, and matrix tortuosity.

1.2 UNSATURATED ZONE TRANSPORT

In contrast to the homogenous transport pathway in the stylized human intrusion borehole, the unsaturated zone radionuclide transport model is consistent with a conceptual description of the stratigraphy, as detailed in SAR Section 2.3.2.3.1, which includes subsurface formations of heterogeneous layers of anisotropic fractured volcanic rocks. This heterogeneity, which is largely determined by the geologic setting, affects the distribution of flow and radionuclide transport in the unsaturated zone. The heterogeneity results from alternating layers of welded and nonwelded ash-flow and ash-fall tuff. Syndepositional processes, such as welding, fracturing, and formation of lithophysal cavities, along with such postdepositional processes as hydrothermal alteration, faulting, and additional fracturing, control the heterogeneous distributions of hydrologic properties in the unsaturated zone. The combined result of these processes is a spatially variant flow field where the zones of faster and slower radionuclide travel times to the saturated zone have developed, as noted below. The rate of flow and the extent of transport in fractures are influenced by characteristics such as orientation, aperture, asperity, spacing, fracture length, connectivity, and the nature of any linings or infills. Further discussion of the impact of fractures on radionuclide migration in the unsaturated zone is presented in SAR Section 2.3.8.2.2.1.

As discussed in SAR Section 2.3.8.1, this natural heterogeneity in the stratigraphy and associated hydrologic properties influence the unsaturated zone flow and transport processes. In particular, the low matrix permeability of the zeolitic Calico Hills nonwelded (CHn) unit beneath the northern half of the repository block promotes fracture flow and/or lateral diversion towards faults. In contrast, the unaltered, vitric CHn unit beneath the southern region of the repository block has a relatively high matrix porosity and permeability, and matrix flow dominates. As a consequence, radionuclides released from the northern region of the repository tend to have much shorter travel times to the saturated zone than those released in the southern region because transport is primarily downward through fractures and faults with higher transport velocities as opposed to much slower matrix flow. Discussion of the impact of these hydrogeologic characteristics on radionuclide migration through the unsaturated zone is presented in SAR Section 2.3.8.4.5.1.

In the unsaturated zone, the welded units are structurally more competent, and are characterized by a higher fracture density and better developed fracture network (faults, joints, random fractures) than the nonwelded units. Open fractures create a secondary porosity that results in a higher net permeability in the welded units than in the nonwelded units, and the open fractures create avenues of preferential flow and fast transport pathways in comparison to matrix flow. To construct a numerical model consistent with this conceptual description, a dual-permeability numerical flow model was selected to incorporate the processes likely to affect transport. Fracture networks are modeled as a highly permeable continuum with low porosity, while the matrix is modeled as a much less permeable continuum with higher porosity. In this context, fracture porosity is the total volume of voids designated as fractures divided by the total volume, rather than an interstitial porosity within the individual fractures themselves. Fluid exchange between the fracture and matrix continua is simulated using an active fracture model, and the fracture–matrix interaction includes diffusive exchange of radionuclides. Advective transport of solutes in fractures is included, whereas retardation due to sorption in fractures is conservatively not included, except in fault zones, where the medium is treated as a fracture continuum with low effective porosity, and sorption on the rock surfaces. Colloid transport accounts for the fast transport of some radionuclides in fractures.

In fractured rock systems, the fracture connectivity is a dominant factor in controlling fluid flow and associated solute transport. Within unsaturated fractured rock, the nonlinearity associated with unsaturated fluid flow in conjunction with the heterogeneity of the fracture structure at different scales is expected to give rise to a significant degree of preferential flow, even in a well-connected fracture network (Liu et al. 1998). Due to the preferential flow, only a fraction of the fractures within an unsaturated connected fracture network would contribute to water flow. The reduction of the number of fractures through which water is actively flowing reduces the number of surfaces through which the matrix diffusion of radionuclides from the flowing water is taking place. In addition, the fracture–matrix interface area across which diffusion takes place can be considered to be a function of the effective saturation in the active fracture. The radionuclide transport within the matrix and concentration gradient at the fracture–matrix interface are also impacted by the increased effective fracture spacing. Preferential flow is simulated in the unsaturated zone flow and transport models using the AFM proposed by Liu et al. (1998). According to the AFM, the fraction of active fractures in a connected network of fractures, f_a, can be determined as a function of the effective saturation, S_e, and γ, a positive constant dependent on properties of the fracture network, as follows:

$$f_a = S_e^{\gamma} \qquad \text{(Eq. 1)}$$

The effective saturation is defined as a function of the fracture saturation, S_f, and the residual saturation, S_r, as follows:

$$S_e = \frac{S_f - S_r}{1 - S_r} \qquad \text{(Eq. 2)}$$

Implementation of the AFM, as presented by Liu et al. (1998), is reflected in adjustments made to (1) the interface area across which fluid flow and/or matrix diffusion take place and (2) the mean spacing between flowing fractures. Liu et al. (1998) present an interface area reduction factor that decreases the effective area across which fluid flow or matrix diffusion between the fractures and rock matrix take place. This effective interface area reduction factor includes the influence of both changes in the interface area and changes in the spacing between flowing fractures. The interface area reduction factor R, as defined by Liu et al. (1998), is:

$$R = \left(\frac{A_{fm,a}}{A_{fm}}\right)\left(\frac{n_{f,a}}{n_f}\right)\left(\frac{d}{d_a}\right) \cong S_e^{1+\gamma} \qquad \text{(Eq. 3)}$$

In Equation 3, the first term represents the ratio of the active fracture's fracture–matrix interface area, $A_{fm,a}$, for the AFM, which is a function of the effective saturation of the active fracture and the representative fracture-matrix interface area, A_{fm}, to the representative fracture-matrix interface area. Thus, the first term takes into consideration the influence of effective saturation on the fraction of the representative interface area that is available for diffusion. Note that this reduction in the effective interface area associated with effective saturation is considered in the AFM even when all fractures are active ($\gamma = 0$). The second term is the ratio of the number of active fractures, $n_{f,a}$, to the number of fractures, n_f, which is equal to f_a, as defined in Equation 1. The third term represents the adjustment to the fracture spacing, where d is the mean spacing between all fractures and d_a is the spacing between active fractures.

As noted in *Particle Tracking Model and Abstraction of Transport Processes* (SNL 2008b, Section C5), the interface area reduction factor R represents the ratio of the radionuclide diffusive fluxes for the uncorrected (non-AFM) and corrected (AFM) cases, and addresses both the interface area and the transport length scale associated with the distance between the flowing fractures. To put the impact of the active fracture model on matrix diffusion in perspective, Equation 3 can be solved using the TSPA model's median fracture saturation for the 10th percentile present-day climate of approximately 0.01756, a residual saturation of approximately 0.01, and assuming the value of γ to be 0.4, which is the mean value from the TSPA model uncertainty distribution (SNL 2008a, Addendum 01, Section 6.5.6). Applying these parameters to Equation 3 would generate an interface area reduction factor of approximately 0.0011, which would effectively reduce the diffusive fluxes at the fracture–matrix interface by three orders of magnitude. This effective decrease in matrix diffusion interface area associated with flow along preferential flow paths (active fractures) is in contrast to the single fracture conceptualization used in the stylized human intrusion borehole model where matrix diffusion takes place across the entire perimeter of a single fracture.

1.3 RADIONUCLIDE TRAVEL TIMES

The rate of radionuclide transport is a function of: the characteristics of individual radionuclides; the form in which the radionuclide is released (dissolved or colloidal); the hydrogeologic conditions in the flow paths, which in turn is a function of release location; and the uncertainties associated with transport parameters (SAR Sections 2.3.8.5.4 and 2.3.8.5.5). According to model simulations presented in SAR Section 2.3.8.5.5, in regions where the mobile radionuclides travel through fast fracture flow paths (approximately the northern half of the repository block), mean transport times for non-sorbing species through the unsaturated zone component of the Lower Natural Barrier are predicted to be in the range of 1 to 100 years (SAR Figure 2.3.8-50) depending on the matrix diffusion coefficient and the flow rates. For a release of a moderately sorbing species such as ^{237}Np within the northern half of the repository block, a sensitivity analysis indicates that mean travel times are from 1 year to greater than 100 years (SAR Figure 2.3.8-51), depending on the matrix diffusion coefficient, the K_d, and the flow rates. For a northern region release of a strongly sorbing species such as any of the plutonium radionuclides, a sensitivity analysis shows that mean travel times are from 5 years to greater than 1,000 years (SAR Figure 2.3.8-53). Because of the influence of flow path short-circuiting through the faults and the decrease in effective matrix diffusion interface area associated with transport along preferential pathways in a network of fractures as simulated using the AFM, travel times for radionuclide releases in the north are expected to be shorter than for the unsaturated zone borehole model. For regions with an intervening layer of high-matrix-permeability rock (approximately the southern half of the repository block), mean transport times for unretarded species range from hundreds to less than 2,000 years (SAR Figure 2.3.8-50). Species that are moderately sorbed, such as ^{237}Np, have mean transport times ranging from less than 5,000 years to greater than 50,000 years (SAR Figure 2.3.8-52). Species that undergo strong sorption (plutonium radionuclides) are delayed for much longer times, with travel times ranging from less than 50,000 years to greater than 500,000 years (SAR Figure 2.3.8-54), or long enough to allow radioactive decay to significantly reduce their mass flux at the water table (SAR Section 2.3.8.5.5.1). Note that the travel times for southern releases are highly correlated with the K_ds and show relatively little correlation with the matrix diffusion coefficient, indicating that travel through the highly permeable matrix of the Calico Hills vitric units is a major controlling factor on transport of radionuclides released in the south.

For comparison with the above predicted travel times through the unsaturated zone component of the Lower Natural Barrier, a modified version of the verification case for the human intrusion borehole transport model described in Section 7.2.4.1.12[a] of *Total System Performance Assessment Model/Analysis for the License Application* (SNL 2008a) was analyzed over the epistemic sample size of 300 realizations. The simulation assumed a release of one kilogram of ^{129}I and ^{237}Np in the first year to the human intrusion borehole. The median transport times for ^{129}I (non-sorbing species) through the unsaturated zone human intrusion borehole from the 300 realization verification case are predicted to be in the range of 416 to 5,320 years (Figure 1) based on the 0.05 and 0.95 probabilities. Note that the median travel times represent the cumulative breakthrough curve times associated with the cumulative release of 50% of the source mass. The median value of the median travel times is approximately 1,240 years. The distribution of breakthrough curves is dependent on the sampled values of the matrix diffusion coefficients and the borehole flow rates used in the human intrusion analysis (Figure 2). The results for ^{129}I indicate that the transport times are consistent with the range of transport times predicted for southern releases in the unsaturated zone transport model for non-sorbing species presented in SAR Figure 2.3.8-50; the 80th percentile value of the median human intrusion borehole transport time for ^{129}I is at 2,100 years (Figure 1), with the longest median transport times occurring from releases from the repository subregion with the lowest percolation rates, for the 10th percentile infiltration case. For ^{237}Np (a moderately sorbing species), the median transport time ranges from less than 1,590 years to greater than 100,000 years (Figure 3) based on the 0.05 and 0.95 probabilities, with the median value of the median transport times at approximately 12,000 years. The results for ^{237}Np are consistent with the range of transport times predicted for southern releases to the unsaturated zone transport model for moderately sorbing species, presented in SAR Figure 2.3.8-52, and highly correlated with the sampled K_ds. The 80th percentile value of the median human intrusion borehole transport time for ^{237}Np is at approximately 64,000 years, with the longest median transport times occurring from releases within the repository subregion with the lowest percolation rates for the 10th percentile infiltration case (Figure 4).

The travel times through the unsaturated zone borehole in the Human Intrusion Scenario are consistent with the travel times estimated for the unsaturated zone component of the Lower Natural Barrier, when both the fracture- and the matrix-dominated regions are considered, although they are longer than travel times for northern releases that are dominated by horizontal flow into faults with relatively fast downward groundwater velocities. These median travel time results reflect the large ratio of matrix diffusion interface surface area to the water volume in the fracture associated with the relatively slow matrix diffusion processes in the human intrusion borehole occurring during the very short advection-based travel through the fractures.

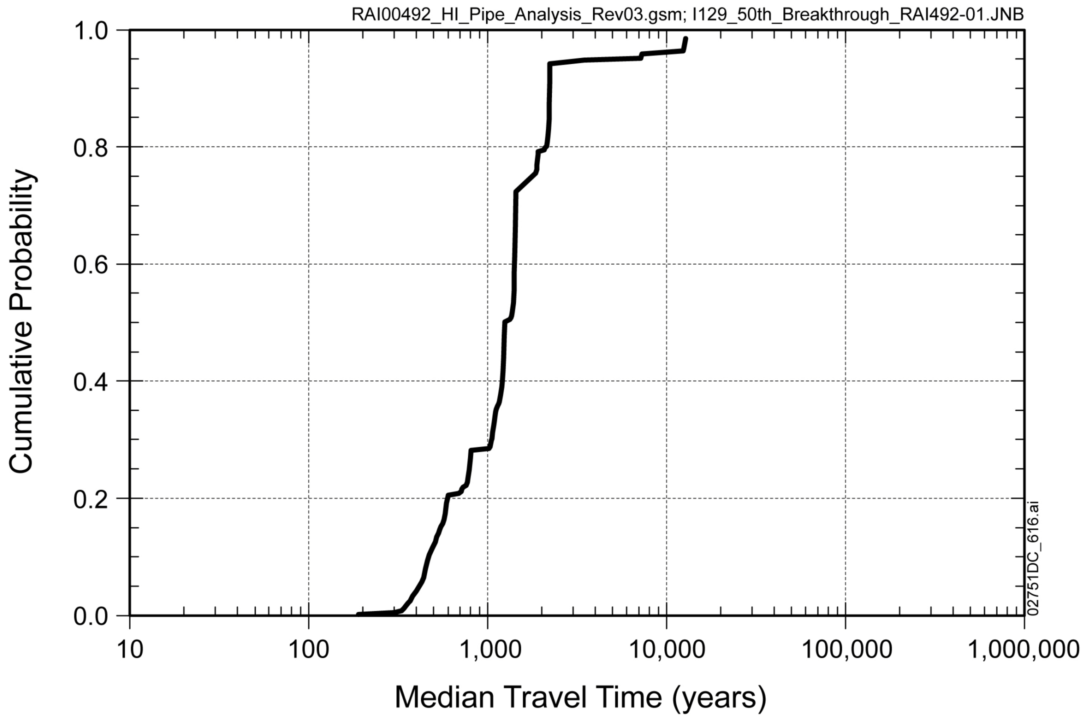

Figure 1. Cumulative Distribution Function of ^{129}I Median Travel Time through the Human Intrusion Borehole (300 epistemic samples)

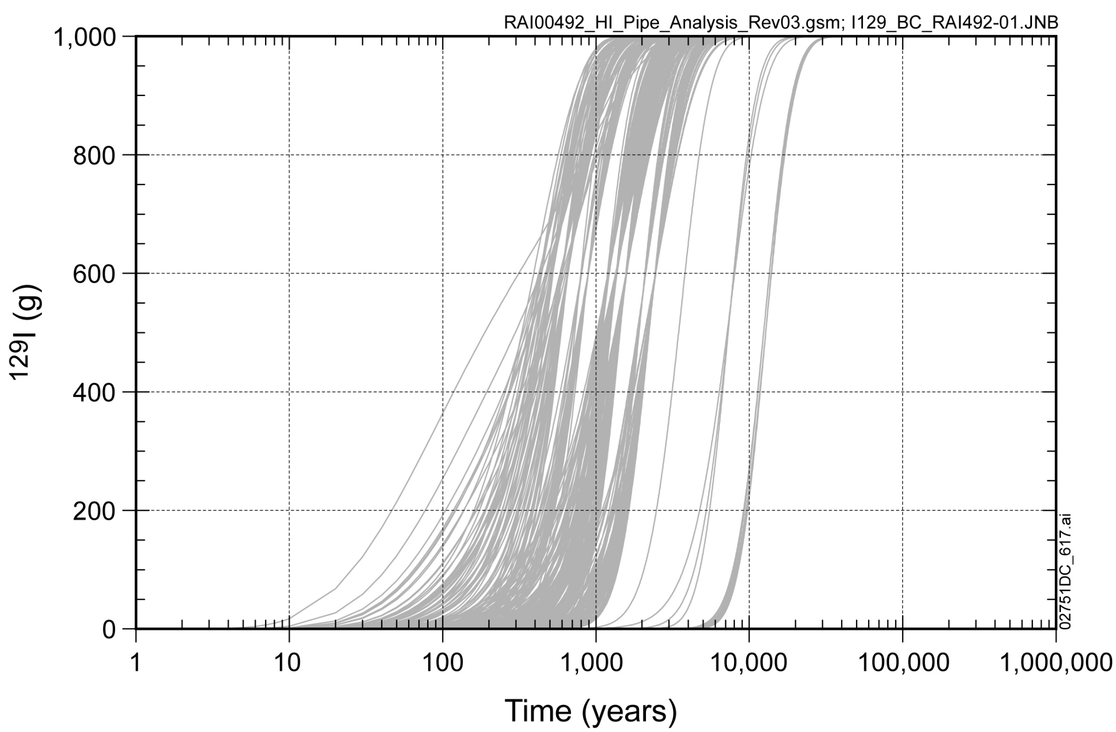

Figure 2. Human Intrusion Borehole Unsaturated Zone Breakthrough Curves for ^{129}I (300 epistemic samples)

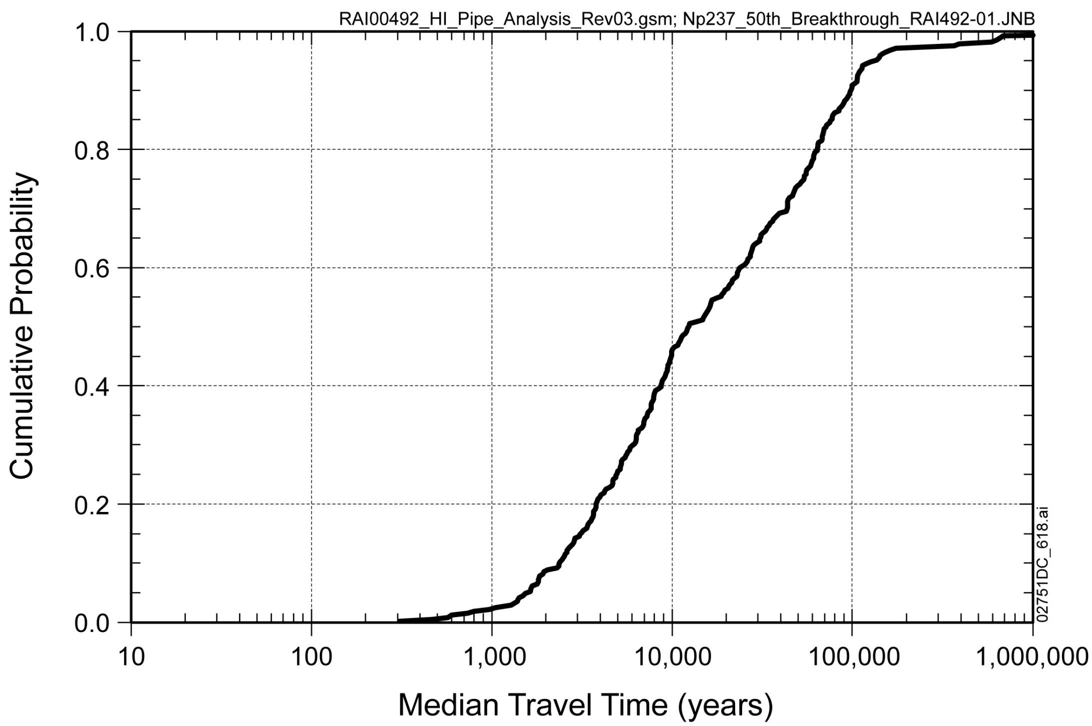

Figure 3. Cumulative Distribution Function of ^{237}Np Median Travel Time through the Human Intrusion Borehole (300 epistemic samples)

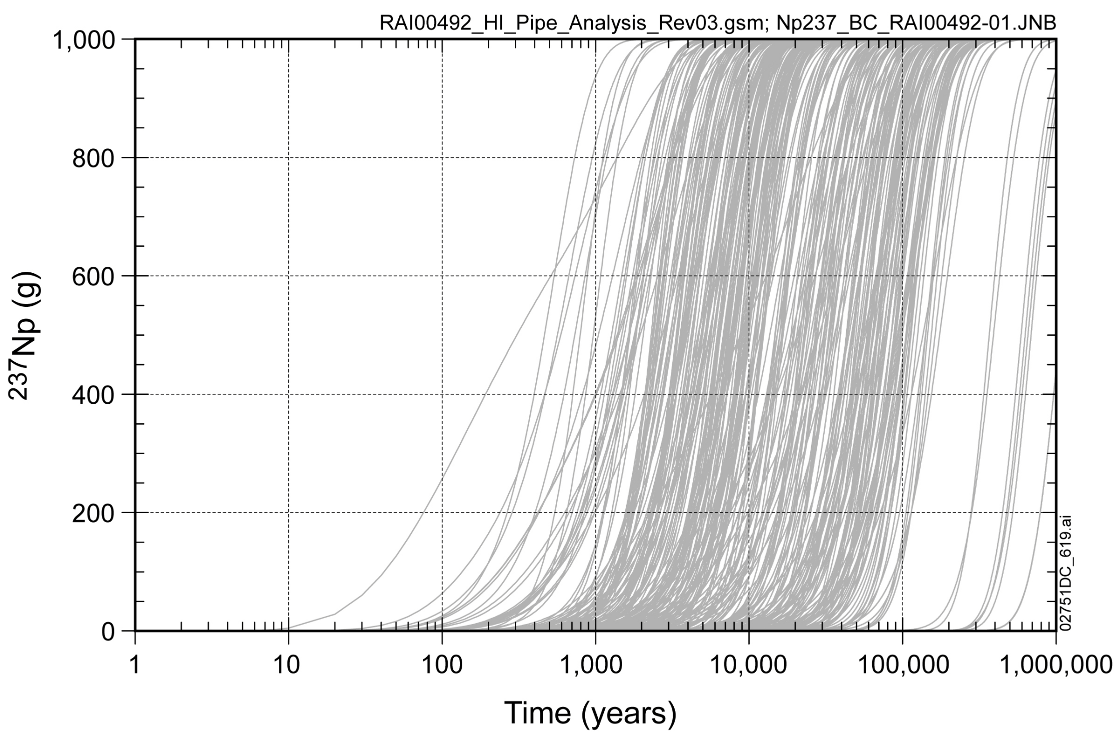

Figure 4. Human Intrusion Borehole Unsaturated Zone Breakthrough Curves for ^{237}Np (300 epistemic samples)

1.4 SUMMARY

The AFM model is used for radionuclide transport though the unsaturated zone component of the Lower Natural Barrier. Transport through unsaturated zone fracture network with preferential pathways (active fractures) is considered. The AFM results in a decrease in the effective surface area for fracture-matrix interactions. The decrease in the effective surface area accounts for the shorter average travel times through the unsaturated zone when compared with the radionuclide travel times through the human intrusion borehole when using the same unsaturated zone host rock properties. In addition, the radionuclide travel times through the human intrusion borehole are consistent with the upper range of predicted mean radionuclide travel times in the unsaturated zone model.

2. COMMITMENTS TO NRC

None.

3. DESCRIPTION OF PROPOSED LA CHANGE

None.

4. REFERENCES

Liu, H.H.; Doughty, C.; and Bodvarsson, G.S. 1998. "An Active Fracture Model for Unsaturated Flow and Transport in Fractured Rocks." *Water Resources Research, 34,* (10), 2633-2646. Washington, D.C.: American Geophysical Union.

SNL (Sandia National Laboratories) 2007. *UZ Flow Models and Submodels.* MDL-NBS-HS-000006 REV 03 AD 01. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20080108.0003.

SNL 2008a. *Total System Performance Assessment Model/Analysis for the License Application.* MDL-WIS-PA-000005 REV 00 AD 01. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20080312.0001.

SNL 2008b. *Particle Tracking Model and Abstraction of Transport Processes.* MDL-NBS-HS-000020 REV 02 AD 02. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20080129.0008.