2/12

PROBABILISTIC PERFORMANCE ASSESSMENT OF A BOREHOLE OR SHAFT WITH A DEGRADED SEAL

Randall D. Manteufel and Mikko P. Ahola
Center for Nuclear Waste Regulatory Analyses
Southwest Research Institute
San Antonio, TX 78238-5166

ABSTRACT

A set of probabilistic calculations are reported which assess the importance of a degraded borehole or shaft seal on post-closure repository performance. The analyses are based on a set of generic steps taken in a probabilistic performance assessment: (i) conceptually identifying the issues related to the process or phenomena specifically being investigated, (ii) developing specific conceptual models which identify quantitative measures of performance, (iii) developing simplified mathematical models for the conceptual models, (iii) developing probability distribution functions that describe model parameter variability, (iv) performing probabilistic calculations (e.g., Monte Carlo simulations), (v) evaluating and interpreting the probabilistic results, and (vi) providing feedback and recommendations to other groups in the High-Level Waste (HLW) program.

A degraded shaft or borehole seal was identified as a possible transport pathway accelerating either gaseous or aqueous phase flow from the repository (where radionuclides will be released) to the accessible environment. Simple models of buoyancy- and gravity-driven flows were developed for the gaseous and aqueous transport, respectively. The fluid particle travel time from the repository to the ground surface was selected to be the performance measure for gaseous flow, and from the repository to the water table for the aqueous flow. A hypothetical borehole was modeled as extending a random depth from the ground surface towards, and possibly into, the water table. Both gaseous and aqueous streamlines were assumed to transmit the length of the borehole and the pertinent geologic media. Mathematical models were developed to predict the travel times, and important parameters were identified (e.g., depth of borehole, hydrologic properties of a degraded seal, hydrologic properties of the geologic media, and infiltration rates). Probability Distribution Functions (PDFs) for the model parameters were either obtained from the literature or adopted assuming worst-case conditions. Numerical calculations were performed in a probabilistic manner by randomly selecting values from the PDFs and computing the resultant travel time. The results were displayed using scatter plots, and correlations (or lack thereof) were identified. Lastly, the results were interpreted and recommendations developed for site and seal characterization programs.

For the specific conceptual models, selected performance measures, mathematical models, and assumed PDFs of model parameters used in this work, the probabilistic calculations of travel time suggest that the seals may not be important pathways. It is also suggested that the hydrologic properties of seals have a relatively minimal impact on performance when compared with the effects from other variables. For gaseous travel time, the bulk conductivity of the geologic medium has a much stronger impact on performance. For aqueous phase travel time, the infiltration rate has a much stronger impact on performance. In an effort to give an unbiased assessment of seals, the models employed in this work were chosen to be of the same level of detail as those employed in the Iterative Performance Assessment (IPA) Phase 2 exercise recently completed by the Nuclear Regulatory Commission (NRC) (Wescott et al., 1994).

1 INTRODUCTION

Site characterization activities at the proposed high-level radioactive waste repository at Yucca Mountain (YM), Nevada will result in numerous boreholes being drilled at various locations and depths to gather data for characterizing the hydrologic, geochemical, structural, and seismic properties of the underground environment. There are approximately 191 existing and 322 proposed boreholes within the YM region, varying in depth from very shallow (1.5 m) to very deep (1,830 m), and having diameters from 0.15 to 0.45 m (Fernandez et al., 1994). The current site characterization plan calls for the excavation of an Exploratory Studies Facility (ESF) (DOE, 1993). Preliminary versions of the advanced conceptual designs of the repository and ESF presently call for two vertical shafts, namely a fresh air intake shaft and an exhaust shaft. These two shafts may be as large as 6 m in diameter, and will be required mainly because of federal regulations requiring separate ventilation circuits in both the waste emplacement and construction (drift) development areas of the repository.

As a result of these site characterization activities, as well as future repository activities and performance confirmation monitoring, there will be numerous openings created into the mountain from both the surface as well as underground. Both the Department of Energy (DOE) and the NRC have investigated the sealing of shafts and boreholes, in order to evaluate the effectiveness of seals on postclosure repository performance (Case and Kelsall, 1986; Daemen et al., 1983; Fernandez and Freshley, 1983; Fernandez et al, 1987, 1989, 1993, 1994; Ouyang and Daemen, 1992; Ran and Daemen, 1991; DOE, 1993). A basic concern about shafts and boreholes is that they may become preferential pathways for gaseous or liquid flow. In this paper, we report a probabilistic performance assessment that investigates the impact of a poorly sealed borehole (or shaft) that is located within the vicinity of the repository block itself, and extends towards the water table (where the shaft terminates at the repository horizon).

The current regulations for seal performance require that "Seals for shafts and boreholes shall be designed so that following permanent closure they do not become pathways that compromise the geologic repository's ability to meet the performance objectives" (10 CFR 60.134). The compliance with such regulations requires sufficient knowledge of the long-term performance of seals. Analyses of the long-term performance of seals are needed in order to evaluate their potential impact on meeting the repository performance objectives (10 CFR Part 60.112 and 60.113(a)(1)). There is considerable uncertainty in long-term seal performance because of the potential for complex coupled thermal-mechanical-hydrological-chemical (TMHC) processes. Thus, in developing its License Application Review Plan (NRC, 1994), the NRC identified two Key Technical Uncertainties (KTUs) with seals and seal performance. As a result of these KTUs, the NRC staff will likely conduct independent interpretations of DOE data and descriptions or utilize independent models developed or obtained by the NRC to investigate the effects of seal degradation on repository performance.

In the analysis, two different cases are considered: (i) gaseous phase flow from the repository to the ground surface, and (ii) aqueous phase flow from the repository to the underlying water table. It is assumed in both analyses that the seals are present, but degraded. The analyses are carried out using an approach and models consistent with those used in previous Total-System Performance Assessments (TSPAs) (e.g., Codell et. al, 1992; Wescott et al., 1994; Wilson et al., 1994). Another purpose of this analysis is to identify key parameters which have the strongest influence on liquid or gaseous flows. As formulated, the analyses in this work presupposes the seal has degraded and then addresses the question: Do degraded seals enhance fluid flow from the repository (where radionuclides will be released) and to the accessible environment?

2 ISSUES ASSOCIATED WITH SEALS

Figure 1 shows a schematic of a seal/host rock system depicting a disturbed zone due to creation of the borehole or shaft, and a degraded seal. Seals can degrade over time as a result of a number of factors. For instance, since YM is located in the seismically active Basin and Range region of Nevada, repetitive seismic motions over a long period of time could cause significant cracking and perhaps debonding of cementitious seals. The settling of backfill below the primary cementitious seals over time could cause debonding and displacement of the concrete plug from its

3/12

intended location. Heat generated from the decaying waste could also enhance the degradation of seals. This may occur through differential expansion/contraction between the seal materials and the surrounding host rock causing thermally induced cracking within the seals or larger interface gaps. Finally, chemical reactions may enhance the seal degradation. Such reactions may take place within the seal material itself or between the seal and the adjacent host rock. For instance, if the composition of the seal is significantly different from that of the host rock, chemical reactions at the seal interface could create a gap for liquid or gaseous flow. Such reactions may occur much faster when coupled with thermal and hydrologic processes. For cementitious seals, chemical reactions taking place during the curing period could cause expansion or shrinkage, the extent of which could also be affected by the environment (e.g., temperature) in which it is emplaced. As mentioned earlier, there exists a large degree of uncertainty as to the extent of the effect of these coupled processes on the degradation and long-term performance of the seals.

The overall effectiveness of seals also directly depends on the available emplacement technologies. Currently, there appears to be high confidence that methods are available for seal emplacement (Fernandez et al., 1994). This high confidence includes preparation of the hole prior to sealing (i.e., removing casing, removing lodged or abandoned drill bits/equipment, borehole wall conditioning, etc.), based on knowledge gained in the oil industry. This requires that the boreholes and shafts be accurately logged during their construction. On the other hand, there is fairly low confidence that seal testing methods are available to verify seal performance once they have been installed (Fernandez et al., 1994).

3 PROBABILISTIC ASSESSMENT OF SEAL PERFORMANCE

The analyses are designed to mimic the flow calculations performed in the recently completed Iterative Performance Assessment (IPA) Phase 2 exercise (Wescott et al., 1994). As such, these calculations have a distinct PA approach which differs from earlier assessments (Fernandez et. al., 1989). In particular, this assessment evaluates the performance of seals in relation to other phenomena and parameters using flow models that have been used in previous total-system PA activities.

The analyses are based on consideration of both gaseous and aqueous phase flow, as shown in Figure 2. It is expected that gas streamlines will have the characteristics of large-scale buoyant flow, hence the flow will be upward through the repository and directed towards the ground surface. The liquid streamlines will be dominated by downward gravity-driven percolation. Hence, aqueous phase flow will be predominately downward through the repository horizon and directed towards the water table. Although the flow systems may be dynamic and change over the time period of interest, in the IPA Phase 2 exercise it was assumed that the aqueous phase flow was steady-state and primarily through vertical columns which intercepted sections of the repository. Hence we consider vertical columns with upward gaseous flow and downward aqueous flow.

Alternative conceptual models of the flow at YM were not considered in this work, as well as alternative scenarios about the evolution of the geologic setting. It is possible that alternative scenarios can lead to phenomena and processes which are not being considered in the current model.

The fluid particle travel time is a useful performance measure which is used to assess the effects of a degraded seal on the flow system. For gaseous flow, fluid particle travel time over the distance from the repository horizon to the ground surface is of relevance. For aqueous flow, the fluid particle travel time over the distance from the repository horizon to the water table is of importance. It is anticipated that a degraded seal (i.e., more porous and permeable) will lead to shorter travel times, which results in less effective isolation of the waste.

In Figure 3, a hypothetical borehole begins at the ground surface and extends some unknown distance which may be as far down as the water table. A gas streamline is assumed to go through the borehole, thereby maximizing the distance traveled in the borehole and minimizing the distance traveled in the geologic medium. The gaseous conductivity of the degraded seal was assumed to be higher than the host rock, therefore, the travel time from the repository horizon to the ground surface would be reduced.

It is important to note that the distance of interest for the gaseous travel time is only a segment of the total length of the streamline. The distance of interest is from the repository to the ground surface, yet the streamline begins at the ground surface, travels through the geologic medium where it enters the borehole. In order to predict the gaseous velocity through the borehole, one needs to also consider the flow through the geologic medium. For the gaseous calculations, the bulk gaseous conductivity was modeled as uniform throughout the geologic medium.

In Figure 4, a streamline for an aqueous particle is modeled as initiating at the ground surface and extending into the water table. Here, the travel time of interest is from the repository horizon to the water table. For simplicity, it was decided to simulate the flow through only one of the seven vertical columns used in IPA Phase 2 (Wescott et al., 1994). One of the larger areas was selected (area number 2) which consisted of 60 m of Topopah Spring (TS) and 130 m of Calico Hills zeolitic (CH). If a borehole extends below the repository, then the fluid particle can travel within the borehole for that length. If the borehole extends all the way to the water table, then the particle can travel entirely within the borehole and not travel in the geologic medium.

In this analysis, the seal is assumed to degrade from some unspecified causes. It is noteworthy that neither the type of seal nor the source of the degradation was required to perform the analyses. What is required is a characterization of a degraded seal. After reviewing the pertinent literature (Daemen et al, 1983; Ran and Daemen, 1991; Ouyang and Daemen, 1992), it was found that the properties of a functioning seal were frequently available, but the properties of a degraded seal were typically unavailable.

Lacking specific information, worst-case estimates of the degraded seal properties were assumed. The worst type of degradation for a seal is hypothesized to be cracking of the seal material (due to thermal-seismic effects), creation of a gap between the seal material and the geologic material (due to thermal-seismic or chemical effects), and inadequate sealing of fractures in the disturbed zone (created during drilling). Hence, the worst-case estimates of degraded seal properties consisted of relatively conservative estimates of seal "fracture" properties (see Table 1).

The hydrologic properties of a seal were modeled in a fashion similar to the geologic material. The seal was modeled as having fracture and matrix characteristics. It was assumed that the primary degradation mode of a seal was increased effective fracture conductivity. The matrix conductivity of a seal was assumed to remain consistent with the un-degraded seal properties, which are relatively low. As discussed by Fernandez et al. (1994), un-degraded seals typically have conductivities lower than the geologic medium. Therefore, only the fracture properties of a degraded seal were considered important for flow. The matrix properties of a seal were considered comparable to the geologic matrix properties.

Gaseous Travel Time

The gaseous travel time was calculated as the ratio of the length to velocity:

$$TT_{rg} = \frac{L_{rg}}{u_g} \tag{1}$$

where

TT_{rg} = gaseous travel time from the repository horizon to the ground surface,
L_{rg} = length of gaseous streamline from the repository horizon to the ground surface, and
u_g = pore velocity of the gas.

The average pore velocity of a gas particle was calculated assuming buoyancy-driven flow (see Manteufel, 1994).

$$u_g = \frac{g_c \ \beta \int_w^g \Delta T \ dz}{\phi \ \nu \left(\frac{L_{hr}}{K_{hr}} + \frac{L_{bh}}{K_{bh}} \right)} \tag{2}$$

where

g_c = gravitational constant,
β = thermal volumetric expansion coefficient,
$\int_w^g \Delta T \ dz$ = integral of the vertical temperature profile (in excess of the ambient geothermal temperature profile) from the water table (w) to the ground surface (g),
ϕ = porosity,
ν = kinematic viscosity of the gas,
L_{hr} = length of gaseous streamline throughout the host rock,
L_{bh} = length of gaseous streamline through the borehole which has a degraded seal,
K_{hr} = gaseous conductivity of the host rock, and
K_{bh} = gaseous conductivity of the degraded seal in the borehole.

The buoyant force is related to the increased rock temperatures due to the emplacement of the heat-generating waste. The thermal output from the waste and the resulting vertical temperature profile are time-dependent, however, these aspects were not of primary concern in this work. Attention was focused on the affects of L_{hr}, K_{hr}, L_{bh} and K_{bh} on the gaseous travel time.

$$TT_{rg} = TT_{rg}(L_{hr}, K_{hr}, L_{bh}, K_{bh}) \tag{3}$$

Representative values were chosen for the parameters in Equation 2 (Wescott et al., 1994), so that a simplified mathematical model was developed.

$$TT_{rg} = \frac{\frac{L_{hr}}{K_{hr}} + \frac{L_{bh}}{K_{bh}}}{\left(\frac{12 \ \text{m}}{\text{yr} - \text{Darcy}} \right)} \tag{4}$$

In Figure 5 and in Table 1, Probability Distribution Functions (PDFs) are presented for the two lengths and two conductivities needed in Equation 4. The depth of the borehole (L_{bh}) ranged from 0 to 600 m (which is the assumed distance from the ground surface to the water table). The distance of gaseous flow in the host rock (L_{hr}) was a maximum of 1,200 m minus the distance traveled in the borehole. As the borehole depth increased, L_{hr} decreased.

The numerical calculations were performed in Monte Carlo fashion where L_{hr}, K_{hr}, and K_{bh} were randomly selected from their respective PDFs, L_{hr} was computed, and then the travel time was computed (using Equation 4). In total, 100 simulations were performed, and TT_{rg} was observed to range over four orders of magnitude (from 1 to 10,000 yr). The number of simulations (e.g., 100) was selected heuristically as being enough to adequately illustrated the correlation between the input parameters and the performance measure.

Scatter plots of the results are shown in Figure 6. The scatter plots show the correlation between the input parameters (i.e., L_{bh}, L_{hr}, K_{hr}, and K_{bh}) and the gaseous travel time (TT_{rg}). The parameter with the strongest correlation was K_{hr}, and both L_{hr} and L_{bh} had negligible correlation. The performance of the seal (measured by its degraded gaseous conductivity) does have an impact on TT_{rg}, however, the correlation is not very strong. A linear curve fit between TT_{rg} and K_{bh} indicated a correlation of 0.029 (r-squared) compared with a correlation of 0.987 between TT_{rg} and K_{hr}.

The reason for the strong correlation between TT_{rg} and K_{hr} is that the minimum distance traveled in the host rock (L_{hr}) is 600 m (i.e., the deepest borehole is one that extends into the water table, $L_{bh} = 600$ m). This is because the gaseous streamline is assumed to begin at the ground surface and descend below the repository horizon where it can enter the borehole. As such, a significant resistance to flow is always attributed to the host rock. In comparison, the resistance to flow in the degraded seal is significantly less than in the host rock (2 decades difference in the means of K_{bh} and K_{hr}). The net result is that K_{hr} is the most important parameter to influence TT_{rg}.

Aqueous Travel Time

For aqueous phase flow, the travel time from the repository horizon to the water table, TT_{rw}, was the performance measure chosen to investigate the importance of seals. The aqueous flow calculations were consistent with those reported in the NRC IPA Phase 2 report (Wescott, et. al., 1994). The Phase 2 aqueous flow calculations were based on steady-state flow which occurred in one of seven tubes each having two legs: first from the ground surface through an unsaturated vertical leg until it reached the water table, and then through a saturated horizontal leg until it reached the accessible environment (at 5 km). The vertical columns were selected to entirely cover the repository. Lateral diversion of flow was considered in the calculations, but was found to have a relatively small effect in changing the percolation fluxes through the columns.

In IPA Phase 2, a number of distinct hydrogeologic units were considered for each of the seven columns. After consideration, only one column was modeled in this work. The one column modeled consisted of 60 m of TS ($L_{ts} = 60$ m) and 130 m of CH ($L_{ch} = 130$ m) between the repository horizon and the water table.

The computation of the TT_{rw} considers two hydrogeologic units and a borehole with a degraded seal. The borehole may penetrate a portion of the TS unit, or penetrate the TS unit entirely and a portion of the CH unit. For each unit, the liquid flux in the matrix is the lessor of the infiltration and the saturated matrix conductivity.

$$Q_m = \min(Q_{inf}, K_m) \tag{5a}$$

where

Q_m = liquid flux in the matrix [mm/yr],
Q_{inf} = infiltration [mm/yr], and
K_m = saturated matrix conductivity [mm/yr].

If Q_{inf} is less than K_m, then the matrix can transmit all of the downward percolating water, and

5/12

there is no flow in the fractures. If Q_{inf} exceeds K_m, then the excess flow goes into the fractures.

$$Q_f = \max(0, Q_{inf} - K_m) \tag{5b}$$

where

Q_f = aqueous phase flux in the fractures [mm/yr].

If Q_f exceeds the saturated fracture conductivity, then either ponding or lateral flow occurs. Because the fracture conductivity (K_f) is typically much larger that Q_{inf} (which is always larger than Q_f) the capacity for fractures to transmit percolating water was never exceeded. A check was performed in the calculations, and it found that for all of the calculations, $K_f > Q_f$. The fraction of the flow in either the matrix or fracture was then computed.

$$f_m = \frac{Q_m}{Q_{inf}} \tag{6a}$$

$$f_f = \frac{Q_f}{Q_{inf}} = 1 - f_m \tag{6b}$$

where

f_m = fraction of flow in the matrix, and
f_f = fraction of aqueous phase flow in the fractures.

The pore fluid velocity was used in the travel time calculations, and is related to the Darcy flux and the porosity as follows.

$$u_m = \frac{Q_m}{\phi_m} \tag{7a}$$

$$u_f = \frac{Q_f}{\phi_f} \tag{7b}$$

where

u_m = matrix pore velocity,
u_f = fracture pore velocity,
ϕ_m = matrix porosity, and
ϕ_f = fracture porosity.

If a borehole penetrates a portion of the hydrogeologic unit, then the length of the unit is reduced by the length of the borehole.

$$L_{ts-bh} = \max(0, L_{ts} - L_{bh}) \tag{8a}$$

$$L_{ch-bh} = \max(0, L_{ch} + L_{ts} - L_{bh}) \tag{8b}$$

The travel times through the TS and CH units were computed as a weighted average to account for both matrix and fracture flow in each unit.

$$TT_{ts-bh} = \left(\frac{f_{m,ts}}{u_{m,ts}} + \frac{f_{f,ts}}{u_{f,ts}} \right) L_{ts-bh} \tag{9a}$$

$$TT_{ch-bh} = \left(\frac{f_{m,ch}}{u_{m,ch}} + \frac{f_{f,ch}}{u_{f,ch}} \right) L_{ch-bh} \tag{9b}$$

The travel time in the borehole with a degraded seal was computed in a similar manner where both matrix and fracture flow was considered. From a performance viewpoint, the possibility of increased fracture flow in the degraded seal was assumed to be of primary concern. For matrix flow, the intact matrix conductivity of the seal was assumed to be either lower than the matrix conductivity of the host rock, or to be comparable to the host rock. As such, matrix flow in the degraded seal was assumed to be the same as for host rock. The primary difference was in the fracture flow.

The fracture pore velocity through the degraded seal was calculated as follows.

$$u_{f,bh} = \frac{Q_{f,bh}}{\phi_{f,bh}} \tag{7b}$$

where

$u_{f,bh}$ = fracture pore velocity in the degraded seal,
$Q_{f,bh}$ = fracture flux in the degraded seal (= $Q_{inf} - Q_m$), and
$\phi_{f,bh}$ = fracture porosity in the degraded seal.

The travel time through the borehole was then

$$TT_{bh,ts} = \left(\frac{f_{m,ts}}{u_{m,ts}} + \frac{f_{f,ts}}{u_{f,bh}} \right) L_{bh,ts} \tag{9c}$$

$$TT_{bh,ch} = \left(\frac{f_{m,ch}}{u_{m,ch}} + \frac{f_{f,ch}}{u_{f,bh}} \right) L_{bh,ch} \tag{9d}$$

where

L = length of borehole in Topopah Spring [= $\min(L_{ts}, L_{bh})$], and
$L_{bh,ch}$ = length of borehole in Calico Hills [= $\max(0, L_{ch} + L_{ts} - L_{bh})$].

The total aqueous travel time is then the summation of the constituent travel times

$$TT_{rw} = TT_{bh,ts} + TT_{ts-bh} + TT_{bh,ch} + TT_{ch-bh} \tag{10}$$

PDFs for each of the parameters used to compute TT_{rw} are shown in Figure 7. A uniform distribution was assumed for the length of the borehole below the repository. An exponential distribution with a mean of 0.5 mm/yr was assumed for the infiltration (from Wilson et al., 1994). The PDFs for the hydrogeologic parameters were obtained from the IPA Phase 2 report (Wescott et

6/12

al., 1994). No degraded seal properties were found in the literature. Therefore, the authors assumed properties which appeared to be worst-case estimates for degraded seals, yet remained plausible. The methodology for developing derived hydrologic parameters described in the Sandia National Laboratories (SNL) TSPA-93 (Wilson et al, 1994) was used to guide the selection of degraded seal properties. The fracture porosity PDF was selected to be a log-beta distribution with values similar to those reported in Table 7-19 of Wilson et al, (1994) (i.e., min = –4.0, max = –1.0, alpha = 1.5, and beta = 2.0). The fracture conductivity of a degraded seal was assumed to be log-normally distributed with a mean of 10^8 mm/yr and a standard deviation of one decade. Numerical calculations were performed in a Monte Carlo fashion with values selected at random from the model parameter PDFs. The TT_{rw} was then calculated for a total of 100 Monte Carlo runs.

Scatter plots of TT_{rw} versus each of the independent model parameters are presented in Figure 8. From the plots, it is observed that infiltration has the strongest effect on TT_{rw}. Below an infiltration of approximately 0.3 mm/yr, TT_{rw} is very large (on the order of 10,000 yr), and above this value, TT_{rw} is much shorter (on the order of 800 yr). This is explained by the matrix/fracture characteristics of the geologic medium. For low values of infiltration, the flow can be accommodated in the matrix. The matrix conductivity for the TS and CH are mainly below 0.3 mm/yr and 0.1 mm/yr, respectively. From the scatter plot, a transition can be seen where the flow begins to go into the fractures above ~0.3 mm/yr. The fractures have extremely large conductivities, hence they have a large capacity to transmit the flow. In addition, the fracture porosity is very small, hence, the pore velocity in the fractures is large. This leads to shorter travel times.

From the scatter plots, TT_{rw} is observed to have a discernible correlation with fracture porosity of the degraded seal. As the seal porosity increases, TT_{rw} increases because higher porosity leads to lower pore velocities. Otherwise, the length of the borehole and the fracture conductivity of the degraded seal have a negligible correlation with TT_{rw}.

The hydrogeologic properties of the host rock also have a minimal correlation with TT_{rw}. Because the fracture porosities of the host rock were specified as constants (and not PDFs), the scatter plots do not show a correlation. The scatter plots, however, do indicate a dual nature to the TT_{rw} where either it is relatively small or large. The scatter plots have a dumb-bell clustering of points primarily either above or below 1,000 yr. Again, this is attributed to the infiltration exceeding (or not exceeding) the matrix conductivities, which leads to fracture flow and short travel times.

Preliminary conclusions suggested by the scatter plots is that the hydrologic properties of a degraded seal may not have a strong impact on the aqueous fluid particle travel time. This conclusion, however, is strongly influenced by the values of the hydrogeologic properties and the conceptual models. Figure 9 illustrates how changes in the parameter values might lead to alternate conclusions. As long as both the seal and rock fracture conductivities are larger than the infiltration rate (as shown in the top of Figure 9), then the properties of the seal will be relatively unimportant. This was the case for the calculations reported in this paper. However, the same conceptual and mathematical models would have predicted that seals are very important if the ranges of the input parameters were as shown in the bottom of Figure 9. Here, the rock fractures would not be adequate to transmit the seeping groundwater, thereby leading to ponding and/or lateral flow. If a degraded seal were present in this case, it would then allow the vertical transmission of the water. Although a distribution of parameters as illustrated in the bottom of Figure 9 is not supported by the current understanding of the YM site, this does suggest that site characterization activities give attention to potential hydrogeologic units which have relatively low values of fracture conductivity.

5 SUMMARY AND CONCLUSIONS

A set of probabilistic calculations were performed to assess the importance of a degraded seal. The generic steps in these calculations were: (1) development of conceptual models, (2) selection of performance measures, (3) formulation of mathematical models, (4) estimation of model parameters, (5) conduct of probabilistic calculations, (6) interpretation of results, and (7) documentation and feedback. Each of these steps are summarized below.

The first step was to conceptualize both the gaseous and aqueous phase flow systems at YM. The gaseous flow streamlines were thought to be buoyancy-driven and upward-directed through the repository and towards the ground surface. The aqueous flow streamlines were identified to be gravity-driven and downward-directed through the repository and towards the water table.

The second step was to select a performance measure where the presence of a borehole of shaft would affect the flow system. The performance measure chosen was a fluid particle travel time, and it was thought that a degraded seal would lead to shorter travel times. For gaseous flow, this was from the repository (where gaseous radionuclides would be released) to the ground surface. For aqueous flow, this was from the repository to the water table.

The third step was to formulate mathematical models to quantitatively predict the gaseous and aqueous travel times. The models were based on simple streamlines for the fluids. The mathematical models were chosen to be similar to those used in the NRC IPA Phase 2 exercise (Wescott et al., 1994). The aqueous flow model was based on a switch from matrix to fracture flow when the infiltration exceeded the matrix flow capacity. Because the purpose of the model was to investigate the effects of a degraded borehole seal, some of the less-relevant details of the mathematical models were abstracted. One example of this is the temperature-dependent buoyant driving force which depends on both time and thermal-loading strategy. It was decided that this was not crucial to the purpose of the investigation.

The fourth step was to obtain estimates of all of the model parameters such as the depth and hydrologic properties of a borehole with a degraded seal, as well as hydrogeologic properties and infiltration rates. Most (if not all) of these properties have inherent variability (due to the frequently random nature of physical systems) and uncertainties (due to the lack of characterization). This variability and uncertainty was accommodated by using PDFs. The PDFs for the hydrogeologic properties were obtained from the IPA Phase 2 report (Wescott et al., 1994). The infiltration rate PDF was obtained from the recently completed SNL TSPA-93 (Wilson et al., 1994). The PDFs for properties of degraded seals were not available, hence they were hypothesized following an approach outlined in the SNL TSPA-93 (Wilson et al., 1994).

The fifth step was to perform the probabilistic calculations. In this paper, a Monte Carlo approach was used where model parameters were randomly sampled from their respective PDFs and used to calculate the performance measures (TT_{rg}, TT_{rw}). The approach adopted in this paper is a very simple and robust approach. Other approaches such as latin hypercube sampling, are available (e.g., Zimmerman et al, 1990), however, they were not used here.

The sixth step was to interpret and relate the results to the models and parameters. The results were interpreted using scatter plots between the performance measures and the model parameters. The scatter plots offer an easy way to identify correlations. For linear correlations, a linear curve can be fit to the data and the degree of correlation can be quantified (e.g., log TT_{rg} versus K_{hr} for gaseous calculations). For more complicated relations, more sophisticated curve-fits can be established or the visual correlation of results can be identified (e.g., TT_{rw} versus Q_{inf}). For the gaseous calculations, it was observed that the conductivity of the host rock had the

7/12

dominant correlation with TT_{rg}, and the conductivity of a degraded seal had a much lower (yet discernible) correlation with TT_{rg}. These results were explained because the model always assumed a significant length of travel in the host rock. For the aqueous calculations, the infiltration had the highest correlation with TT_{rw}, and the seal fracture porosity had a lower (yet discernible) correlation.

The final step is to document the results and give specific recommendations. From this study, it is recommended that (1) site characterization look for hydrogeologic units or zones which have low matrix/fracture conductivities, and (2) researchers hypothesize or measure hydrogeologic properties of both functioning and degraded seals (especially fracture porosity and conductivity). The last recommendation, however, needs to be only of limited effort and more effort should be expended on generic site characterization of hydrogeologic properties.

The reader is reminded that the preliminary conclusions in this paper are constrained by a number of limiting assumptions, primarily: (i) the use of simple flow models, (ii) the identification of specific performance measures, and (iii) the estimates of property values. As more information becomes available, this analysis (or alternative analyses) should be repeated to assess the importance of boreholes and shafts as potential pathways for accelerated fluid flow.

6 REFERENCES

Case, J.B. and P.C. Kelsall. 1986. *Modification of Rock Mass Permeability in the Zone Surrounding a Shaft in Fractured, Welded Tuff.* SAND86-7001. Albuquerque, NM: Sandia National Laboratories.

Codell, R., and others. 1992. *Initial Demonstration of the NRC's Capability to Conduct a Performance Assessment for a High-Level Waste Repository.* NUREG-1464. Washington, DC: U.S. Nuclear Regulatory Commission.

DOE. 1993. *DOE-NRC Technical Exchange on the Exploratory studies Facility Title II Design.* October 4–5, 1993. Las Vegas, NV: U.S. DOE.

Daemen, J.J.K., and others. 1983. *Rock Mass Sealing – Experimental Assessment of Borehole Plug Performance.* NUREG/CR-3473. Washington, DC: U.S. Nuclear Regulatory Commission.

Fernandez, J.A., and M.D. Freshley. 1983. *Repository Sealing Concepts for the Nevada Nuclear Waste Storage Investigations Project..* SAND83-1778. Albuquerque, NM: Sandia National Laboratories.

Fernandez, J.A., P.C. Kelsall, J.B. Case, and D. Meyer. 1987. *Technical Basis for Performance Goals, Design Requirements, and Material Recommendations for the NNWSI Repository Sealing Program.* SAND84-1895. Albuquerque, NM: Sandia National Laboratories.

Fernandez, J.A., T.E. Hinkebein, and J.B. Case. 1989. *Selected Analyses to Evaluate the Effect of the Exploratory Shafts on Repository Performance at Yucca Mountain.* SAND85-0598. Albuquerque, NM: Sandia National Laboratories.

Fernandez, J.A., J.B. Case, and J.R. Tyburski. 1993. *Initial Field Testing Definition of Subsurface Sealing and Backfilling Tests in Unsaturated Tuff.* SAND92-0960. Albuquerque, NM: Sandia National Laboratories.

Fernandez, J.A., J.B. Case, C.A. Givens, and B.C. Carney. 1994. *A Strategy to Seal Exploratory Boreholes in Unsaturated Tuff.* SAND93-1184. Albuquerque, NM: Sandia National

Laboratories.

Manteufel, R.D. 1994. Large-scale buoyant flow at an unsaturated HLW repository. *Proceedings of the 1994 ASME Winter Annual Meeting*. New York, NY: American Society of Mechanical Engineers.

NRC. 1994. *Draft License Application Review Plan for the Review of a License Application for a Geologic Repository for Spent Nuclear Fuel and High-Level Radioactive Waste, Yucca Mountain Site, Nevada*. Revision 0. Washington, DC: U.S. NRC.

Ouyang, S., and J.J.K. Daemen. 1992. *Sealing Performance of Bentonite and Bentonite/Crushed Rock Borehole Plugs*. NUREG/CR-5685. Washington, DC: U.S. Nuclear Regulatory Commission.

Ran, C., and J.J.K. Daemen. 1991. *Effectiveness of Fracture Sealing with Bentonite Grouting*. NUREG/CR-5686. Washington, DC: U.S. Nuclear Regulatory Commission.

Wescott, R.G., and others. 1994. *Phase 2 Demonstration of the NRC's Capability to Conduct a Performance Assessment for a High-Level Waste Repository*. NUREG-1464. Washington, DC: U.S. Nuclear Regulatory Commission.

Wilson, M.L., and others. 1994. *Total-System Performance Assessment for Yucca Mountain – SNL Second Iteration (TSPA-1993)*. SAND93-2675. Albuquerque, NM: Sandia National Laboratories.

Zimmerman, D.A., K.K. Wahl, A.L. Gutjahr, and P.A. Davis. 1990. *A Review of Techniques for Propagating Data and Parameter Uncertainties in High-Level Radioactive Waste Repository Performance Assessment Models*. NUREG/CR-5393. Washington, DC: U.S. Nuclear Regulatory Commission.

Table 1. Description of Probability Distribution Functions for Parameter Values.

Parameter	Units	Description	Type of PDF	Pertinent Data
GASEOUS PHASE (see Figure 3)				
L_{bh}	m	Length of Borehole from Ground Surface	Uniform	min = 0 max = 600
K_{hr}	Darcy	Conductivity of the Host Rock	LogNormal	Log(mean) = 0 Log(std dev) = 1
K_{bh}	Darcy	Conductivity of Degraded Seal in Borehole	LogNormal	Log(mean) = 2 Log(std dev) = 1
AQUEOUS PHASE (see Figure 4)				
L_{bh}	m	Length of Borehole below Repository	Uniform	min = 0 max = 190
Q_{inf}	mm/yr	Infiltration	Exponential	mean = 0.5
$\phi_{f,bh}$	–	Fracture Porosity of Degraded Seal in Borehole	LogBeta	Log(min)= -4 Log(max) = -1 alpha = 1.5 beta = 2.0
$K_{f,bh}$	mm/yr	Fracture Conductivity of Degraded Seal in Borehole	LogNormal	Log(mean) = 8 Log(std dev) = 1
$\phi_{f,ts}$	–	Fracture Porosity of TS	Constant	0.000041
$\phi_{f,ch}$	–	Fracture Porosity of CH	Constant	0.000046
$K_{f,ts}$	mm/yr	Fracture Conductivity of TS	LogNormal	Log(mean) = 1.6 Log(std dev) = 0.038
$K_{f,ch}$	mm/yr	Fracture Conductivity of CH	LogNormal	Log(mean) = 2.4 Log(std dev) = 0.033
$\phi_{m,ts}$	–	Matrix Porosity of TS	Uniform	min = 0.06 max = 0.16
$\phi_{m,ch}$	–	Matrix Porosity of CH	Uniform	min = 0.20 max = 0.33
$K_{m,ts}$	mm/yr	Matrix Conductivity of TS	LogNormal	Log(mean) = -0.68 Log(std dev) = 0.084
$K_{m,ch}$	mm/yr	Matrix Conductivity of CH	LogNormal	Log(mean) = -1.5 Log(std dev) = 0.28

Note: TS = Topopah Spring
CH = Calico Hills zeolitic

8/12

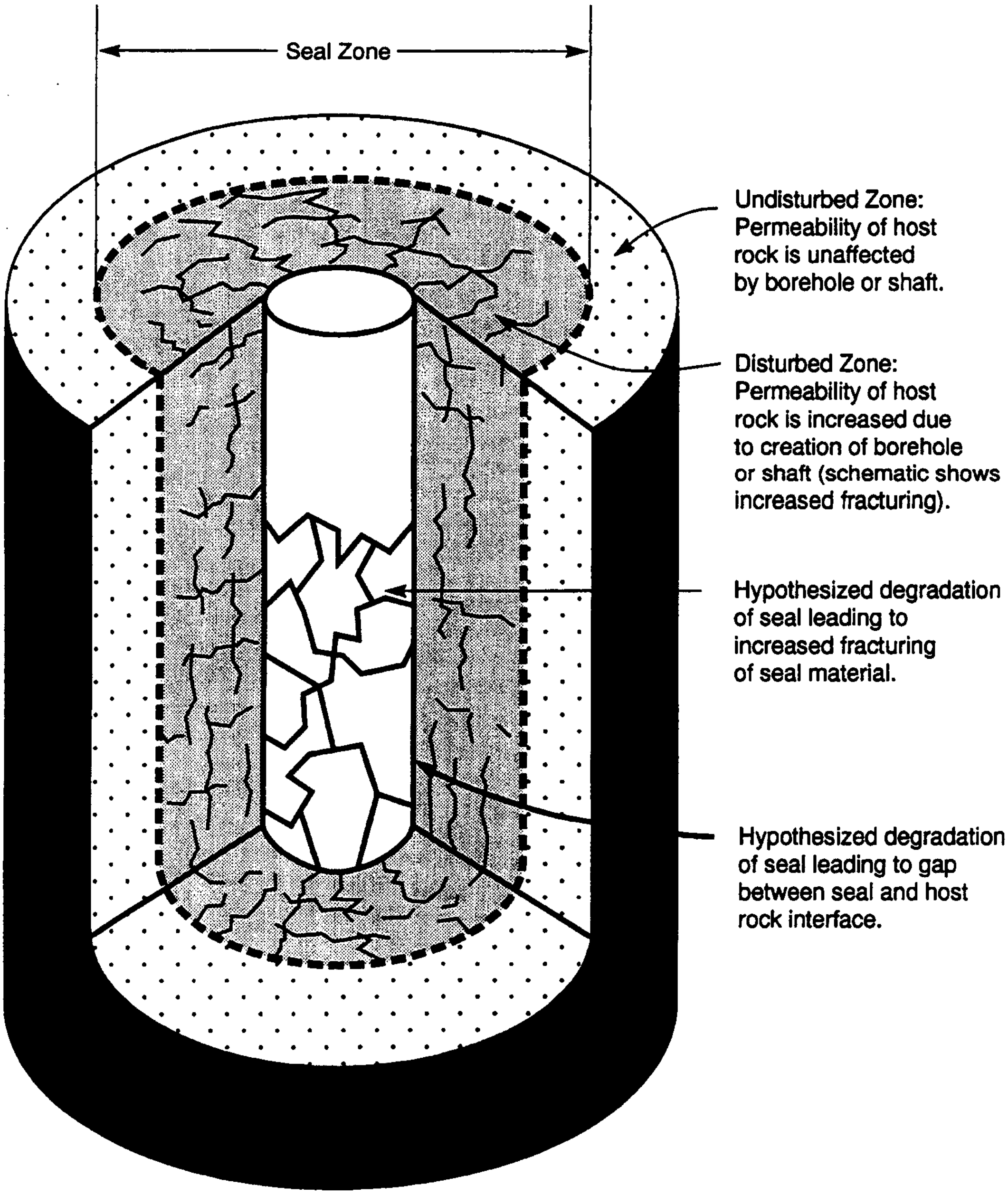

Figure 1. Schematic of the seal/host rock system with typical forms of degradation.

9/12

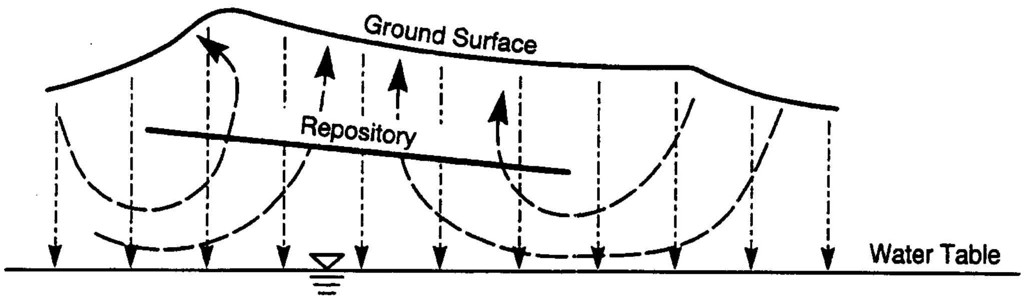

Figure 2. Anticipated gaseous and aqueous phase streamlines through the geologic medium.

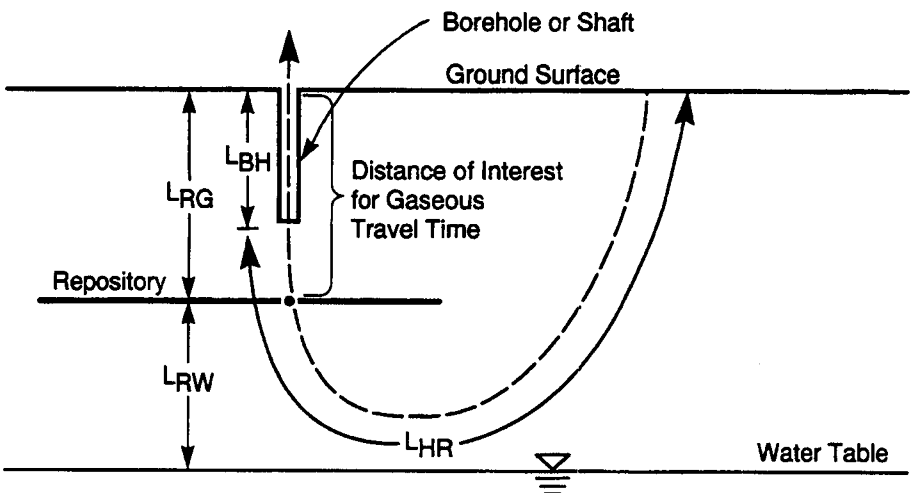

Figure 3. Gas streamline passing through a borehole which has a degraded seal.

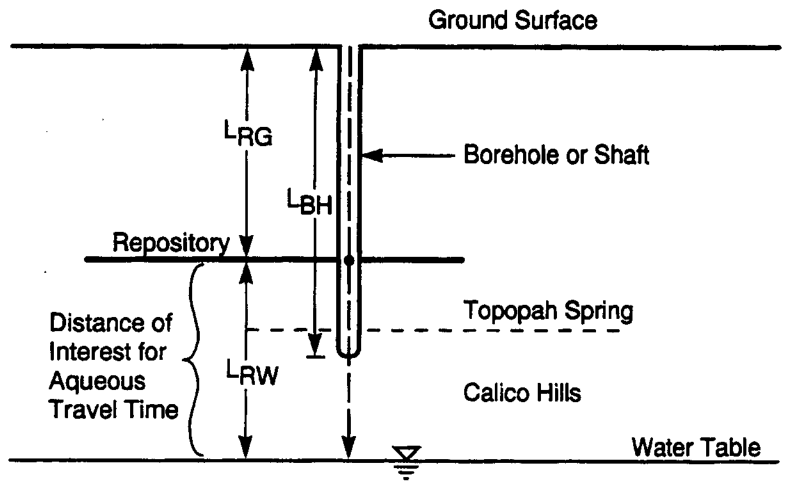

Figure 4. Liquid streamline passing through a borehole which has a degraded seal.

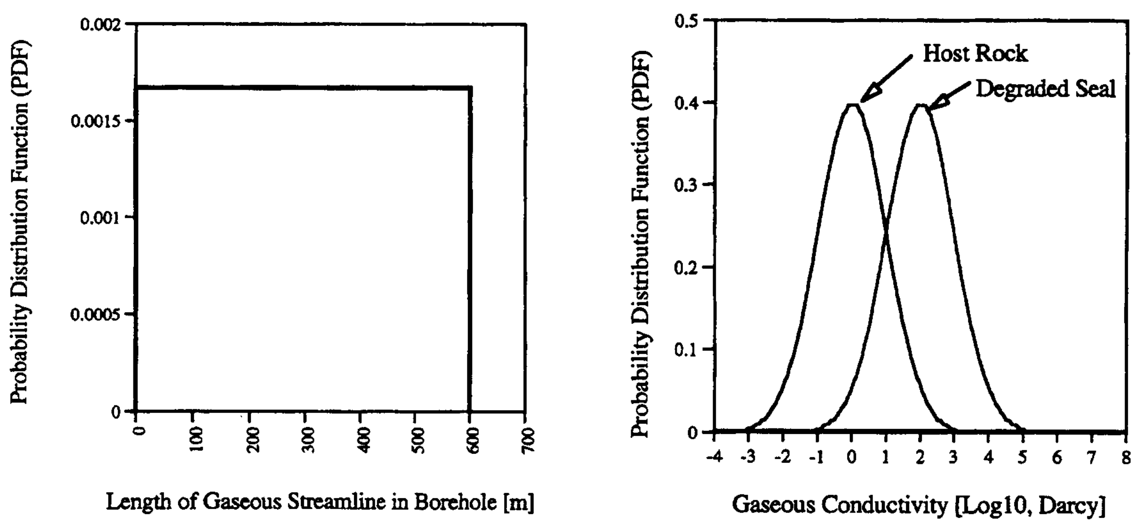

Figure 5. Probability distribution functions for model parameters in the gaseous phase travel time calculations.

10/12

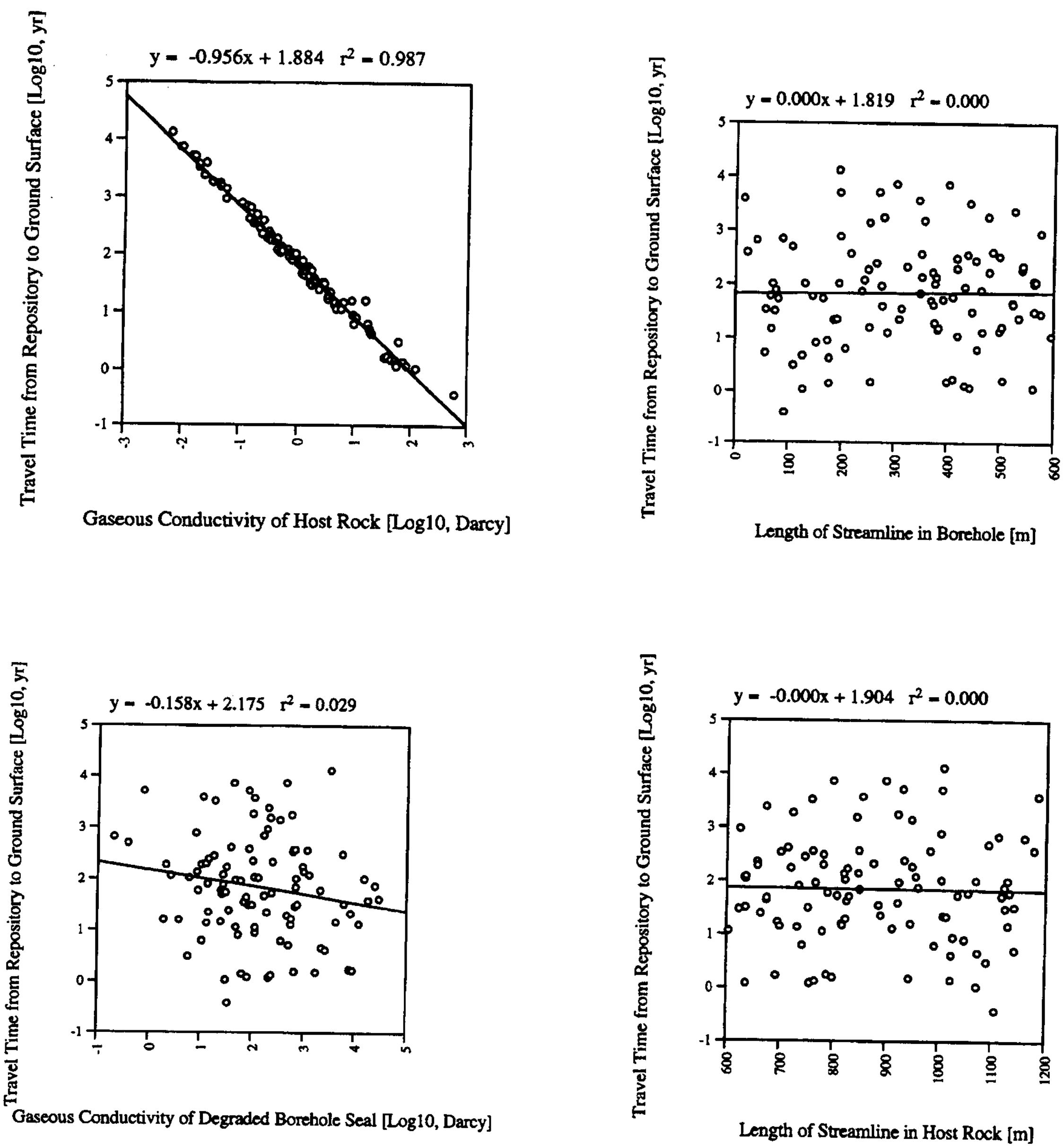

Figure 6. Scatter plots showing the correlation (or lack thereof) between gaseous phase travel time and model parameters.

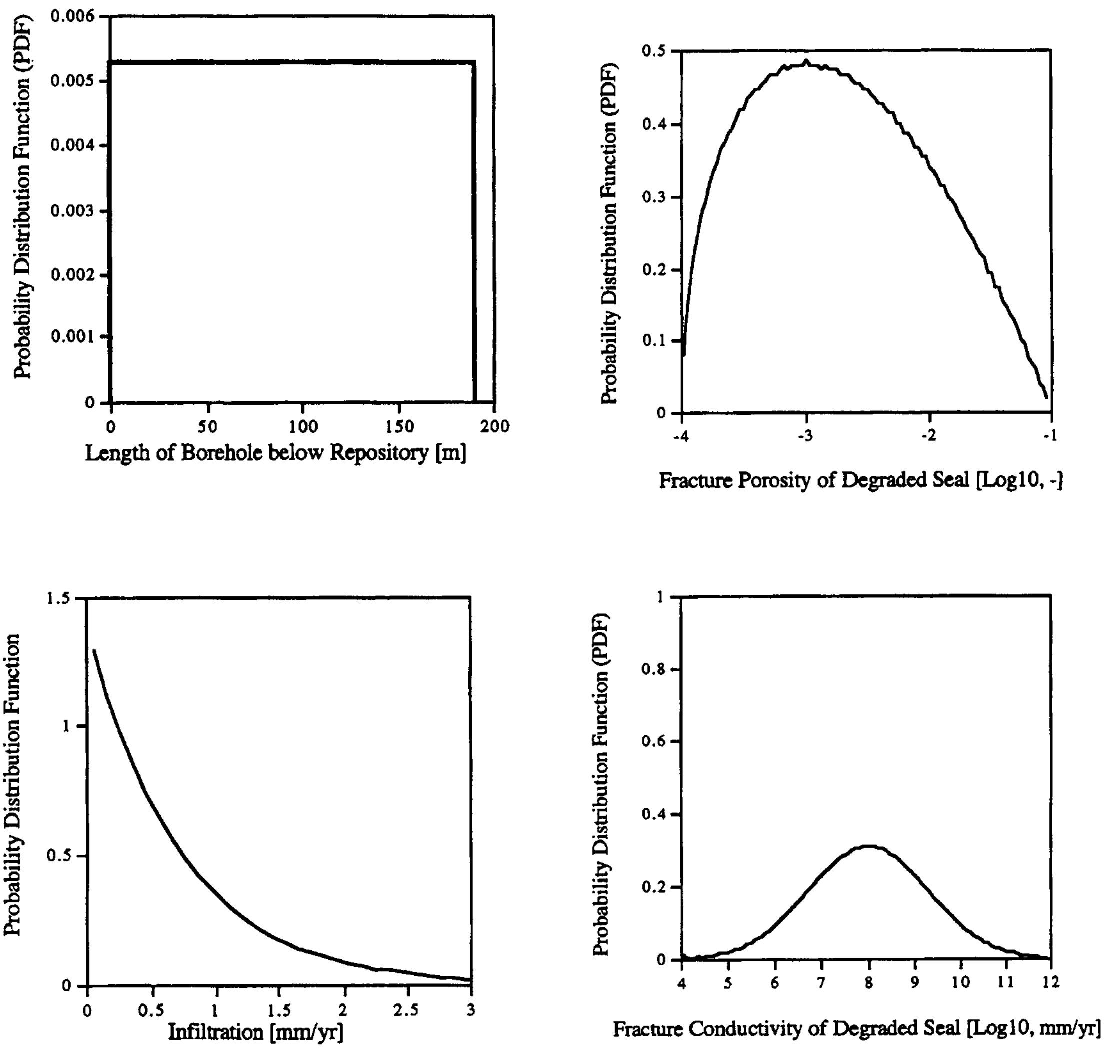

Figure 7. Probability distribution functions for model parameters in the aqueous phase travel time calculations.

11/12

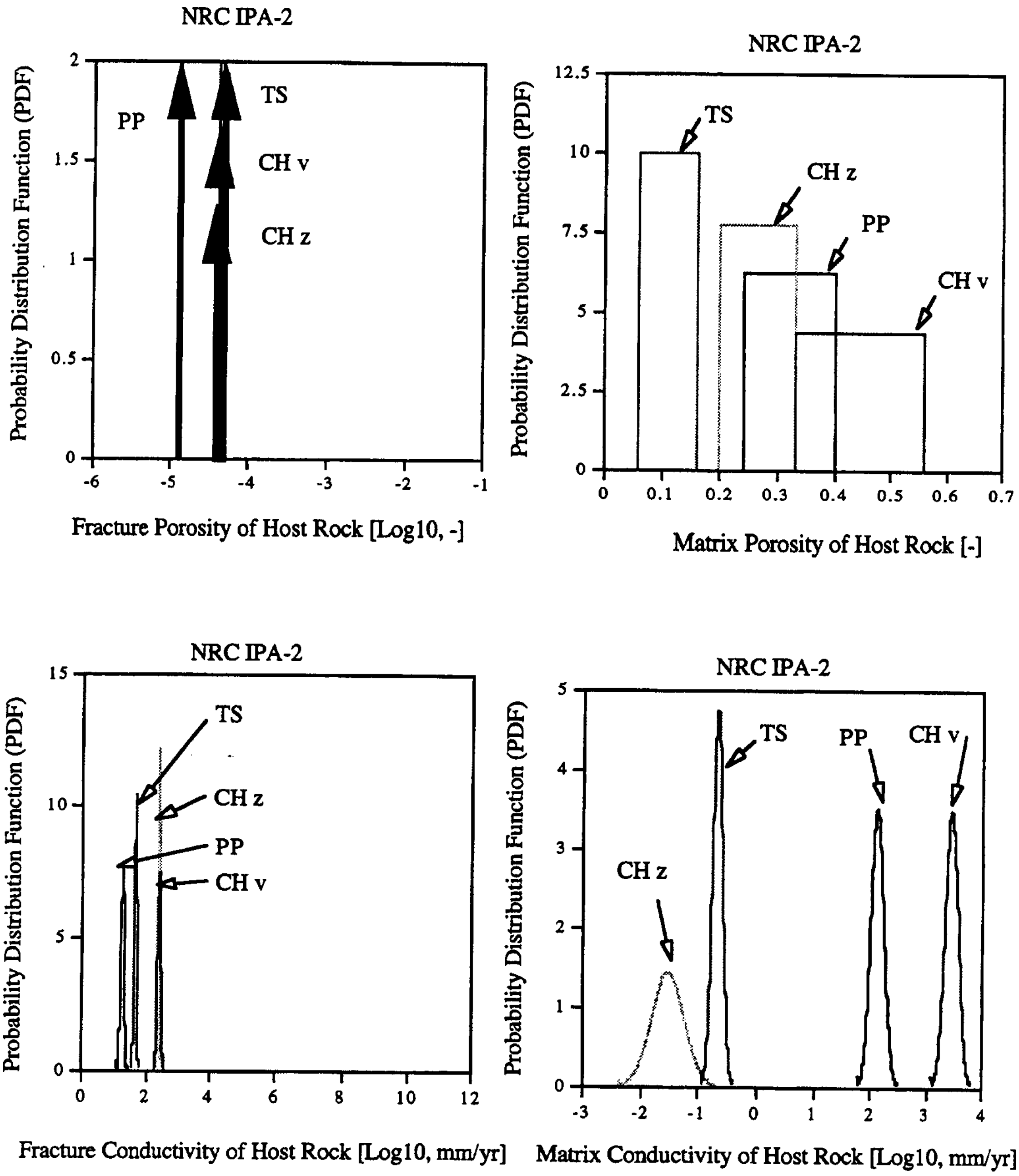

Figure 7 (continued). Probability distribution functions for model parameters in the aqueous phase travel time calculations.

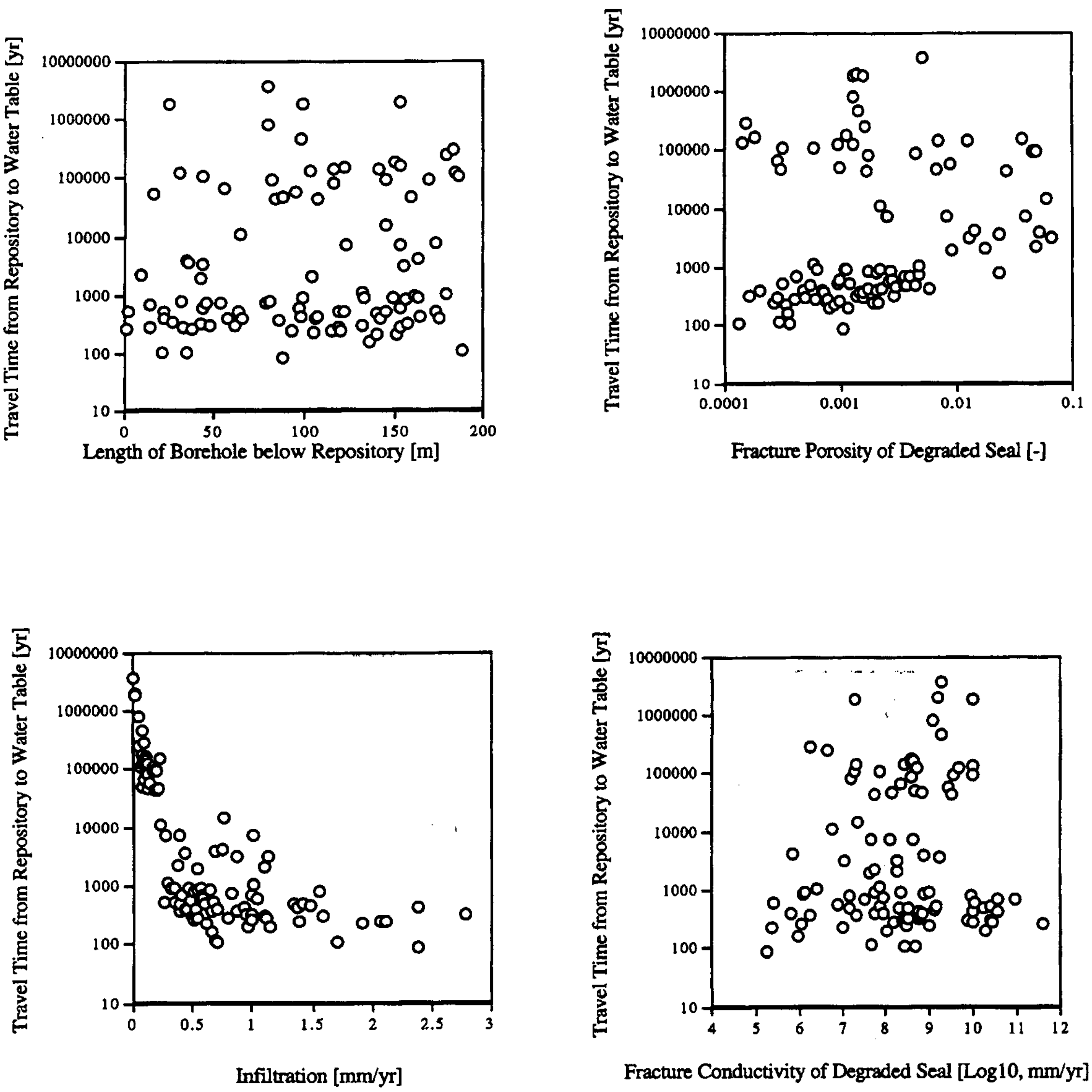

Figure 8. Scatter plots showing the correlation (or lack thereof) between aqueous phase travel time and model parameters.

12/12

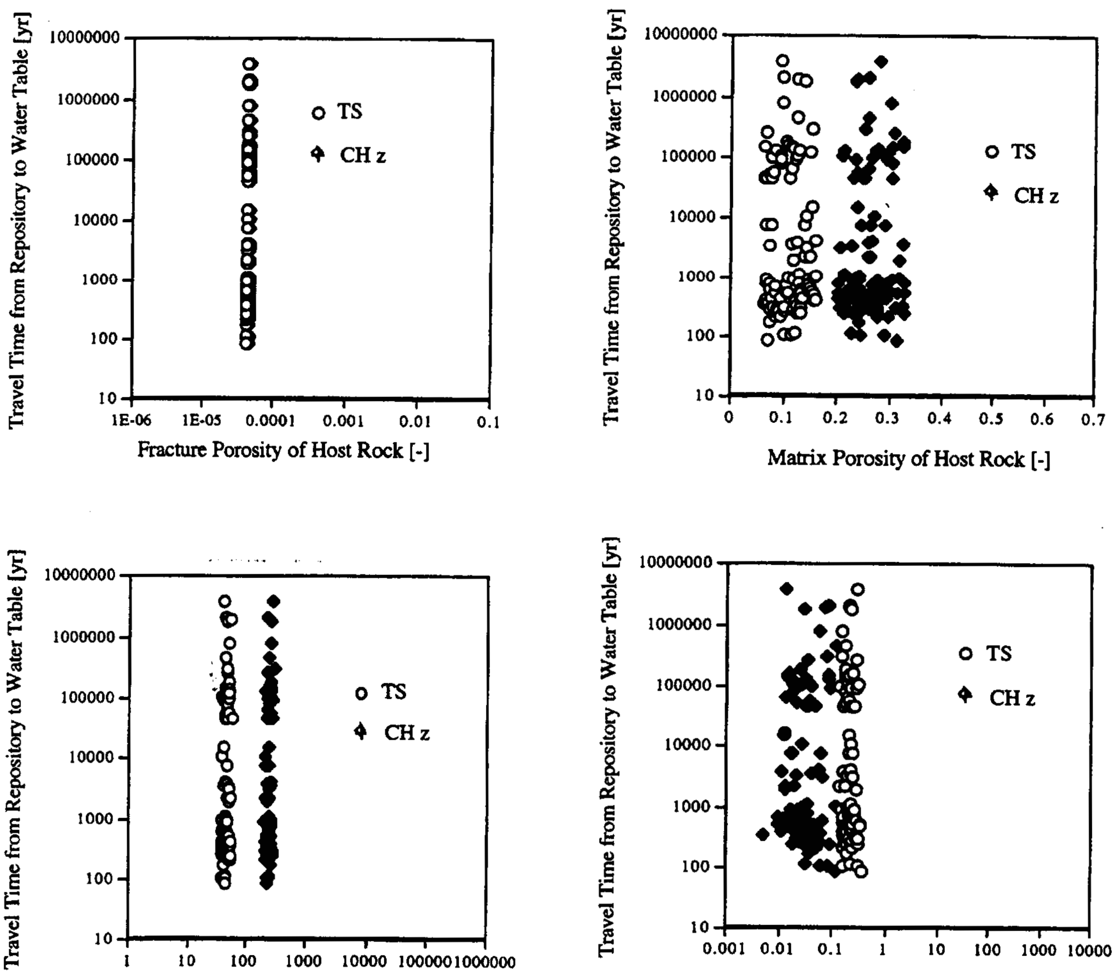

Figure 8 (continued). Scatter plots showing the correlation (or lack thereof) between aqueous phase travel time and model parameters.

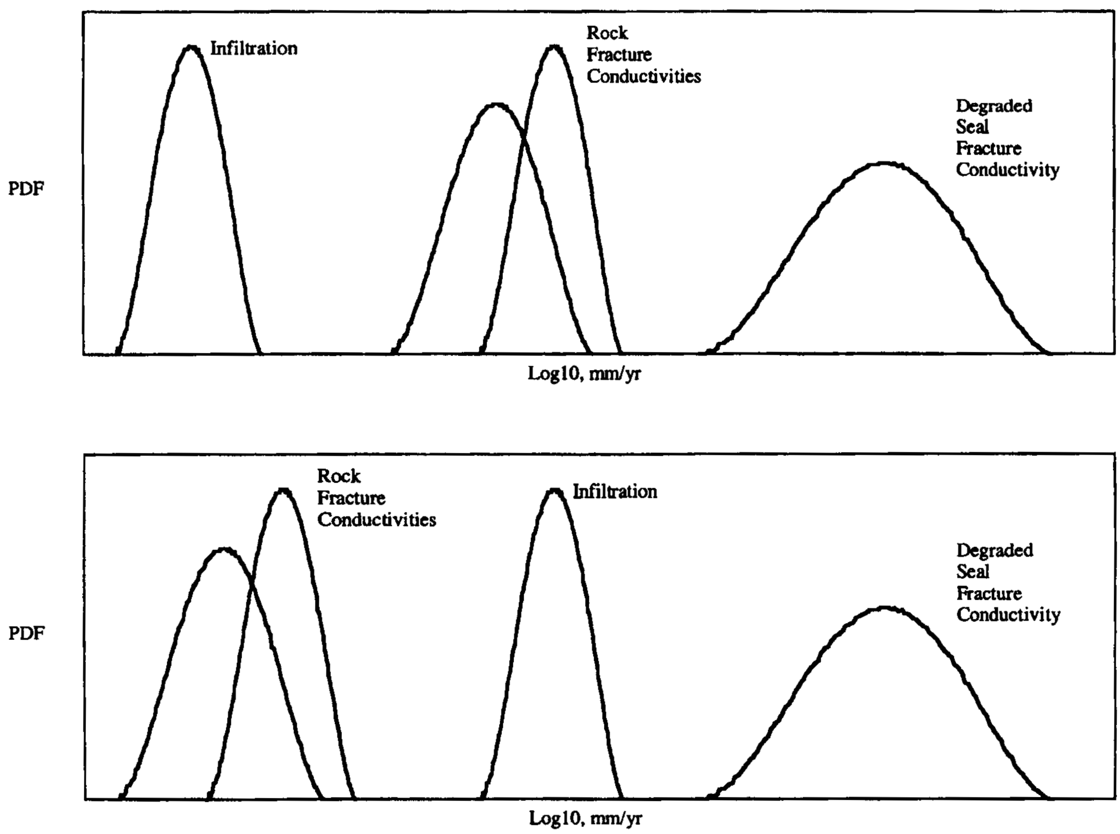

Figure 9. Hypothetical conditions where the seals are relatively unimportant (top) and more important (bottom).