EFFECTS OF UNCERTAINTY AND SPATIAL VARIABILITY ON SEEPAGE INTO DRIFTS IN THE YUCCA MOUNTAIN TOTAL SYSTEM PERFORMANCE ASSESSMENT MODEL

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ABSTRACT

Seepage into the repository drifts is an important factor in total-system performance. Uncertainty and spatial variability are considered in the seepage calculations. The base-case results show 13.6% of the waste packages (WPs) have seepage. For 5th percentile uncertainty, 4.5% of the WPs have seepage and the seepage flow decreased by a factor of 2. For 95th percentile uncertainty, 21.5% of the WPs have seepage and the seepage flow increased by a factor of 2. Ignoring spatial variability resulted in seepage on 100% of the WPs, with a factor of 3 increase in the seepage flow.

INTRODUCTION

Seepage into the repository drifts is an important factor in total-system performance due to its potential to contribute to the degradation of the engineered barrier system, as well as act as an advective transport mechanism for radionuclides. Process level models [1] describe the basic phenomena that control seepage. An abstraction of the process level models [2] is then developed to provide a seepage model that is tractable to implementation into the total-system performance assessment (TSPA) model. Based on the abstraction model, a TSPA seepage model is then developed. Sensitivity studies have been performed on the TSPA seepage model to assess the effects of uncertainty and spatial variability on the number of WPs that are seeped upon and the magnitude of that seepage flow rate.

DESCRIPTION OF SEEPAGE MODEL ABSTRACTION

In the seepage model abstraction, mean seepage flow rate (μ_{Qs}), seepage flow rate standard deviation (σ_{Qs}), and seepage fraction (f_s) are functions of the percolation flux 5 meters above the crown of the drift. These three parameters are uncertain and are represented in the abstraction as triangle distributions (see Table 1). An uncertainty parameter (R) which ranges between 0 and 1 is used to select values from the distributions of mean seepage flow, seepage flow standard deviation, and seepage fraction.

Spatial variability is accounted for in the seepage model abstraction in two ways. First, the seepage flow rate for locations that have seepage is characterized as a beta distribution that is prescribed by the mean and standard deviation of the seepage flow rate, a lower bound of 0.0, and an upper bound of the mean seepage flow plus ten standard deviations. Second, a spatial variability parameter (r) ranging between 0 and 1 is compared to the seepage fraction. If the spatial variability parameter is greater than the seepage fraction, no seepage occurs (i.e., there is no seepage into the drift at the given WP location). If the spatial variability parameter is less than or equal to the seepage fraction, it is divided by the seepage fraction (renormalizing it to between 0 and 1) and the normalized value is used to select the seepage flow from its beta distribution.

The effect of intermediate-scale flow channeling (i.e., between the scales modeled by the site-scale unsaturated-zone-flow process model and the drift-scale seepage process model) is represented in the seepage abstraction model by means of an uncertainty distribution for a flow-focusing factor (*F*) that acts as a multiplier on the percolation flux and an inverse multiplier on the seepage fraction (see Table 2).

Percolation flux time-histories are not provided for all 11,770 WPs in the repository; rather, they are provided for groups of WPs in approximately 600 locations. The locations are grouped, based on a division of the potential repository footprint, into five infiltration-rate bins (see Table 3). Separate percolation flux time-histories are provided for commercial spent nuclear fuel (CSNF) WPs and co-disposal (CDSP) WPs (packages that contain both vitrified high-level waste and special types of spent nuclear fuel). A separate set of percolation flux time-histories is provided for the three infiltration scenarios (low, medium, and high) that are treated in the TSPA model.

Table 1. Uncertainty in Seepage Parameters as Function of Percolation Flux [2]

	Minimum Value			Peak Value			Maximum Value		
q (mm/yr)	f_s	Mean Q_s (m^3/yr)	Std.Dev. Q_s (m^3/yr)	f_s	Mean Q_s (m^3/yr)	Std.Dev. Q_s (m^3/yr)	f_s	Mean Q_s (m^3/yr)	Std.Dev. Q_s (m^3/yr)
0	0	0	0	0	0	0	0	0	0
3.4	0	0	0	0	0	0	0	0	0
5.0	0	0	0	0	0	0	1.97×10^{-3}	3.21×10^{-3}	3.16×10^{-3}
9.9	0	0	0	0	0	0	0.030	0.013	0.014
14.6	0	0	0	2.45×10^{-3}	7.95×10^{-3}	7.09×10^{-3}	0.058	0.023	0.025
73.2	0	0	0	0.250	0.106	0.198	0.744	0.404	0.409
97.9				0.292	0.354	0.366	0.779	0.917	0.733
213	4.91×10^{-3}	0.284	0.188	0.487	1.51	1.15	0.944	3.31	2.24
500	0.060	0.992	1.05	0.925	5.50	4.48	0.999	13.0	5.74
549.2	0.070	1.11	1.20	1.00	6.19	5.05	1.00	14.6	6.33
5383.4	1.00	13	15.7	1.00	73.4	61.1	1.00	177	65.2

Table 2. Uncertainty in the Flow-Focusing Factor (Log-Uniform Distribution)

Infiltration Scenario	Distribution Minimum	Distribution Maximum
Low	1.0	47.3
Mean	1.0	22.4
High	1.0	9.7

Table 3. Distribution of Percolation Flux History Locations

Bin	Fraction of Locations in the Low Infiltration Scenario	Fraction of Locations in the Mean Infiltration Scenario	Fraction of Locations in the High Infiltration Scenario
Bin 1 (0-3 mm/yr)	0.5907	0.01607	0
Bin 2 (3-10 mm/yr)	0.4093	0.13154	0.0123
Bin 3 (10-20 mm/yr)	0	0.32120	0.1340
Bin 4 (20-60 mm/yr)	0	0.52850	0.5480
Bin 5 (60+ mm/yr)	0	0.00269	0.3057

IMPLEMENTATION OF SEEPAGE MODEL ABSTRACTION INTO THE TSPA MODEL

A graphical, object-oriented, computer program (GoldSim 6.04.007 [3]) is used as the integrating shell and statistical framework for linking together the various TSPA component models. The seepage model abstraction is implemented in GoldSim as a dynamically-linked library (DLL) (see Fig. 1).

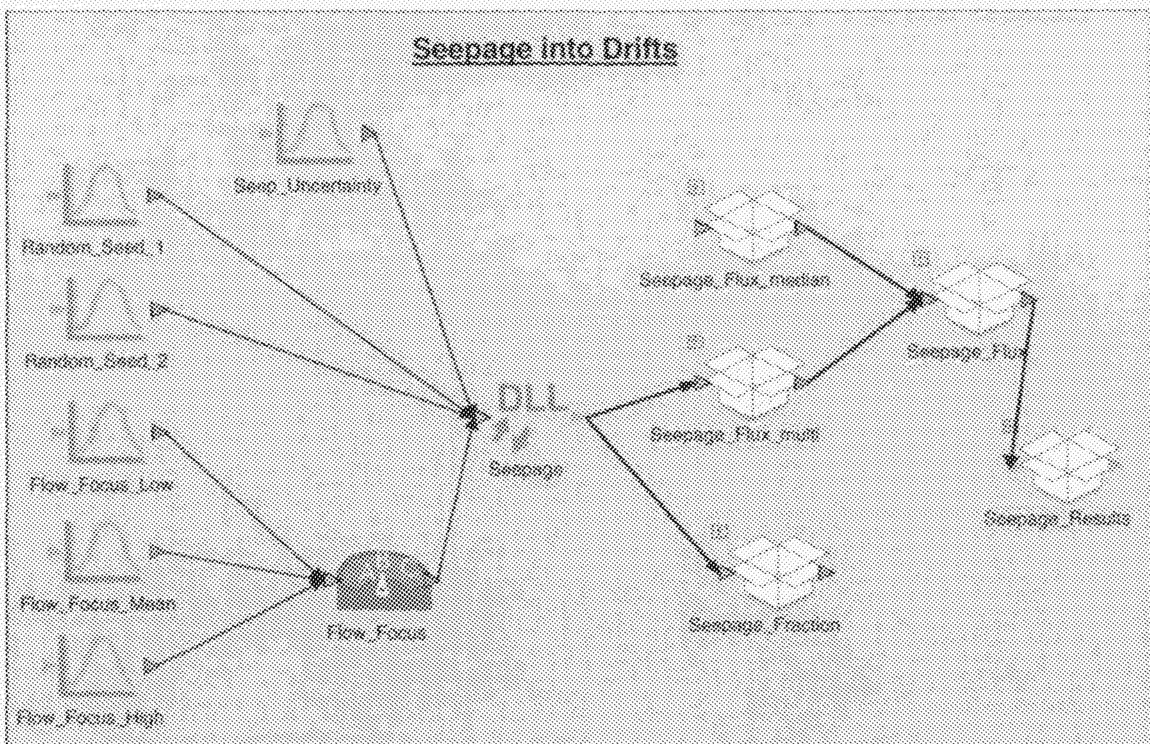

Figure 1. Diagram of the Seepage Model as Implemented in GoldSim.

The uncertainty distributions from the seepage abstraction model (e.g., seepage uncertainty and flow-focusing factor uncertainty) are defined as stochastic parameters in GoldSim. The spatial variability parameter is generated internal to seepage DLL. A pair of random seeds, Random_Seed_1 and Random_Seed_2, are generated in GoldSim and passed to the DLL to be used by the **random_number** function that generates the parameter. This is done so that a different set of random spatial variability parameters are generated for each realization.

The following steps briefly summarize how the seepage DLL calculates seepage flow rate and the fraction of waste packages that see seepage.

1) A random number, R, uniformly distributed between 0 and 1, is generated by GoldSim element *Seep_Uncertainty*. This random number is used to represent the uncertainty in seepage due to the uncertainty in hydrologic properties around the drifts.

2) The flow focusing factor, F, is generated by GoldSim element *Flow_Focus* for the appropriate infiltration scenario (low, mean, or high infiltration).

3) For each location in the repository, the following steps are followed for each waste package type (CSNF or CDSP):

a) A random number, r, uniformly distributed between 0 and 1, is sampled internally to the DLL. This random number is used to represent the spatial variability in seepage and is regenerated each time the program begins to process a new location.
b) The percolation flux, q, is read from the appropriate file.
c) The percolation flux is multiplied by the flow focusing factor, $q' = Fq$.
d) Based on q', the seepage fraction, f_s, is sampled from its triangular distribution using the random number R.
e) The seepage fraction is divided by the flow focusing factor, $f_s' = f_s/F$.
f) If the random number r is greater than or equal to the modified seepage fraction ($r \geq f_s'$), then the seepage flow rate at that location for that time and waste package type is assigned a value of zero.
g) If the random number r is less than the modified seepage fraction ($r < f_s'$), then that location for that time and waste package type will have seepage and the seepage flow rate is determined as follows:

    i) The random number r is re-scaled to $r' = r/f_s'$ so that r' is between 0 and 1.
    ii) Based on q', The mean seepage flow rate, μ_{Qs}, and seepage flow rate standard deviation, σ_{Qs}, are sampled from their triangular distributions using random number R.
    iii) The beta distribution is developed using μ_{Qs} and σ_{Qs}.
    iv) The beta distribution is sampled for the seepage flow rate using random number r'.

h) Repeat steps b through g for each time step in the percolation flux time history.

4) Once step 3 has been completed for each location at each time for each waste package type, the following calculations are performed:

    a) The seepage flow rate at each location is characterized. Locations can have

        i) zero seepage flow at all times (these are locations that never have seepage),
        ii) non-zero seepage flow at some times (these are location that intermittently have seepage),
        iii) non-zero seepage flow at all times (these are locations that always have seepage).

    Note that the term "intermittent" does not necessarily imply that seepage flow turns on and off repeatedly, but only that flow takes place part of the time.

    b) For each bin at each time, an areal-weighted average of the seepage flow for all locations with the same seepage history (i.e., intermittent or always) is calculated for each waste package type.
    c) For each bin, the fraction of locations that have different seepage histories (i.e., never, intermittent, or always) is calculated for each waste package type.

The seepage flow rate results are passed from the DLL to a set of 1-D tables (time versus average seepage flow rate). The fraction of locations that have different seepage histories are passed from the DLL to a set of data elements.

EXECUTION OF THE TSPA MODEL

The TSPA model is designed to be run in a probabilistic manner. Multiple realizations of the model are run with sampled values from the probability distributions of the uncertain model parameters. For this study of the effects of uncertainty and spatial variability on the seepage model uncertainty and variability, 100 realizations of the model were run for each of the following cases.

Table 4. Cases Evaluated to Determine the Effects of Uncertainty and Spatial Variability on the Seepage Model.

Base Case
Fixed Spatial Variability (*r* = 0.001)*
Fixed Spatial Variability (*r* = 0.01)*
Fixed Spatial Variability (*r* = 0.05)*
Fixed Spatial Variability (*r* = 0.10)*
Fixed Spatial Variability (*r* = 0.50)*
Fixed Spatial Variability (*r* = 0.65)*
Fixed Seepage Uncertainty (*R* = 0.05)
Fixed Seepage Uncertainty (*R* = 0.95)
Fixed Flow-Focus Factor Uncertainty (*F* = 5^{th} percentile values)
Fixed Flow-Focus Factor Uncertainty (*F* = 95^{th} percentile values)

* The spatial variability parameter was only held fixed for the comparison to the seepage fraction. The same randomly-sampled values as in the base case were used to evaluate the seepage flow rate from its beta distribution.

Figure 1 shows an example of a seepage flow rate plot. The steady-state seepage from 0 to 50 years, 800 to 2000 years, and 2500 to 100,000 years are due to the steady-state infiltration, and hence percolation flux (q), associated with the climate for those time periods. The rise and decline in the average seepage flow rate between 50 and 600 years is due to the heating of the host rock by WPs upon their emplacement into the repository.

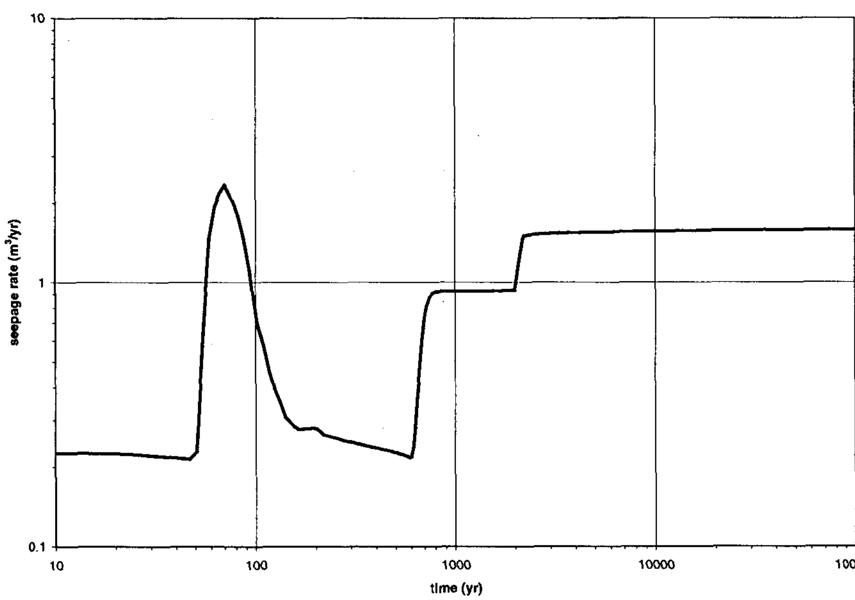

Figure 2. Example Plot of Seepage Flow Rate versus Time (Infiltration Bin 4, Always Seeps).

For a given realization the average seepage flow rate per WP is equal to

$$\overline{Q}_{wp}^{k} = \frac{\sum_{i} \left[n_i \overline{Q}_i \right]_k}{\sum_{i} n_i} \qquad (1)$$

where

$\overline{Q}_{wp}^{k}$ - average seepage flow rate per WP for the kth realization

n_i - number of WPs in the ith environment that has seepage flow

$\overline{Q}_i$ - average seepage flow rate in the ith environment that has seepage flow

The average seepage flow rate per WP over all realizations is equal to

$$\overline{Q}_{wp} = \frac{\sum_{k} \overline{Q}_{wp}^{k}}{N_{Rlz}} \qquad (2)$$

where

$\overline{Q}_{wp}$ - average seepage flow rate per WP for the kth realization

N_{Rlz} - number of realizations

To simplify comparing the cases that were run, only the seepage flow rates at 100,000 years are evaluated. This is a reasonable comparison measure as WPs do not begin to fail in the nominal TSPA case until after 10,000 years [4], and the seepage flow rates are almost constant out past 10,000 years.

RESULTS

The results of the sensitivity cases listed in Table 4 are shown in Table 5.

Table 5. Average Seepage Flow Rate per Waste Package and Average Fraction of Waste Packages that have Seepage.

Case	Average Seepage Flow Rate per WP** [m^3/yr]	Average Percentage of WPs that have Seepage
Base Case	1.170	13.6%
Fixed Spatial Variability – 0.001	3.690	100.0%
Spatial Variability – 0.01	2.120	99.7%
Spatial Variability – 0.05	0.591	78.8%
Spatial Variability – 0.10	0.192	49.6%
Spatial Variability – 0.50	0.001	1.7%
Spatial Variability – 0.65	0.000	0.0%

Fixed Seepage Uncertainty (R = 0.05)	0.480	4.5%
Fixed Seepage Uncertainty (R = 0.95)	2.350	21.5%
Fixed Flow-Focus Factor Uncertainty (F = 5th percentile values)	0.058	22.5%
Fixed Flow-Focus Factor Uncertainty (F = 95th percentile values)	4.240	4.8%

* The spatial variability parameter was only held fixed for the comparison to the seepage fraction. The same randomly-sampled values as in the base case were used to evaluate the seepage flow rate from its beta distribution.

**Note: This average only considers WPs that have seepage (i.e., WPs that have no seepage flow are not considered in the average).

The results from the base case model shows the average percentage of WPs that have seepage to be 13.6%. When spatial variability is set to a very low value (0.001) all WPs have seepage and the average seepage flow rate per package increases from the base case by a factor of 3. All of the WPs having seepage indicates that the spatial variability parameter for any given location was never higher than the seepage fractions for that location. The increase from the base case per WP seepage flow rate is due to all of the WPs having seepage. As the value of the spatial variability parameter is increased, the average flow rate per WP and the average percentage of WPs that have seepage rapidly decrease. This is due to the greater number of locations at which the spatial variability parameter exceeds the seepage fraction.

Fixing the seepage uncertainty at the 5th percentile of its distribution caused a reduction in the average percentage of the WPs having seepage from 13.6% to 4.5% and a factor of 2 decrease in the average seepage flow rate per WP. Conversely, with the seepage uncertainty at the 95th percentile of its distribution, the average percentage of the WPs having seepage increased to 21.5% and the average seepage flow rate per WP increased by a factor of 2. The average seepage flow rate per WP and the average percentage of WPs having seepage show a direct proportional relationship with the seepage uncertainty because the seepage fraction, mean seepage flow rate, and seepage flow rate standard deviation are directly proportional to the seepage uncertainty

Fixing the flow-focusing factor to its 5th percentile value causes the average percentage of WPs having seepage to increase to 22.5%, while the average seepage flow rate decreases by a factor of 20. With the flow-focusing factor fixed at its 95th percentile value the average percentage of WPs having seepage decreases to 4.5%, while the average seepage flow rate per package increases by a factor of 2.5. Since the flow-focusing factor is a multiple to the percolation flux, it is expected that a high flow-focusing factor would result in a higher magnitude of average seepage flow rate per WP. In addition, because the seepage fraction is divided by the flow-focusing factor before it is compared to the spatial variability parameter, it is expected that a high flow-focusing factor would result in a reduction in the average percentage of WPs having seepage.

REFERENCES

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