AN UPDATED FRACTURE-FLOW MODEL FOR TOTAL-SYSTEM PERFORMANCE ASSESSMENT OF YUCCA MOUNTAIN

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ABSTRACT

Improvements have been made to the fracture-flow model being used in the total-system performance assessment of a potential high-level radioactive waste repository at Yucca Mountain, Nevada. The "weeps model" now includes (1) weeps of varied sizes, (2) flow-pattern fluctuations caused by climate change, and (3) flow-pattern perturbations caused by repository heat generation. Comparison with the original weeps model indicates that allowing weeps of varied sizes substantially reduces the number of weeps and the number of containers contacted by weeps. However, flow-pattern perturbations caused by either climate change or repository heat generation greatly increases the number of containers contacted by weeps. In preliminary total-system calculations, using a phenomenological container-failure and radionuclide-release model, the weeps model predicts that radionuclide releases from a high-level radioactive waste repository at Yucca Mountain will be below the EPA standard specified in 40 CFR 191, but that the maximum radiation dose to an individual could be significant. Specific data from the site are required to determine the validity of the weep-flow mechanism and to better determine the parameters to which the dose calculation is sensitive.

BACKGROUND

One concern about locating a high-level radioactive waste repository at Yucca Mountain is that groundwater might not percolate slowly and uniformly through the mountain; rather, it might flow in episodic pulses through the fractures. In this conceptual model of groundwater flow, Yucca Mountain behaves as a sieve, offering waste containers little or no protection from fast-moving streams of water. Some indirect evidence exists for this flow mechanism, but to date the evidence is inconclusive. For example, perched water in the unsaturated zone, possibly implying a weak interaction between flow in the matrix and the fractures, has been observed at Yucca Mountain (at USW UZ-1, and at USW UZ-145), and approximately 20 km southeast of Yucca Mountain at Skull Mountain. Also, at Rainier Mesa, located some 50 km northeast of Yucca Mountain and composed of tuffaceous units similar to those underlying Yucca Mountain, perched water and substantial flow has been observed in faults and fractures in the unsaturated zone.

The first total-system performance assessment conducted by Sandia National Laboratories for the Yucca Mountain Site Characterization Project, TSPA-91, included the analysis of two alternative conceptual models of groundwater flow through the unsaturated zone at Yucca Mountain: slow percolation of water through both the tuff matrix and the fractures (the composite-porosity model), and episodic pulses of water restricted to the fractures (the original weeps model). Recently, a second TSPA iteration was completed, TSPA-93, and this iteration used an improved version of the weeps model. This paper describes the updated weeps model. It is an expansion of the ideas first presented in Gauthier et al. A more detailed treatment of the improvements made to the weeps model is contained in the TSPA-93 report.

THE WEEPS MODEL

Briefly, the weeps model is based on a number of postulates and assumptions, as outlined in Figure 1. In a given time period, a finite amount of precipitation infiltrates Yucca Mountain. This water flows downward, restricted to locally saturated zones, or "weeps." The driving force is gravity; capillary forces of the tuff matrix do not influence flow, possibly due to fracture coatings, capillary barriers, or hysteretic effects. These weeps contact a repository at dis-
All infiltrating water flows gravity-driven downward in locally saturated zones ("weeps")

Nonuniform, episodic infiltration

Weeps contact the repository at discrete points and deterioration occurs only at these points (except for juvenile failures)

Potential Repository

The number of weeps is a function of the amount of infiltrating water, the size of each weep, and the direction of the flow episode.

The distribution of weep sizes is the same as the distribution of fracture sizes; amount of water flowing can be calculated using the parallel-plate model for a fracture

Groundwater travel time through the unsaturated zone is insignificant

Figure 1. Several postulates and assumptions used to form the basis for the weeps model.

crete points. Degradation of waste containers that leads to aqueous releases of radionuclides can occur only at these points, and only during the time period that the flowing weeps contact the containers.

No direct observation or quantitative data exists for weeps at Yucca Mountain. Because of some similarity between Yucca Mountain and Rainier Mesa, we assume that weep flow is through fractures, at least at the repository horizon. The presence of through-going fractures, especially in nonwelded strata, is not critical to the general model.

Because no data exist to determine how the infiltrating water is divided to flow into these postulated weeps, we assume that the weep sizes are directly related to fracture sizes. Fracture sizes are parameterized by aperture and horizontal length. The probability distributions describing these parameters are derived from site data: bulk permeability, fracture frequency, and fracture orientation. Flow through a fracture—i.e., the weep size—is calculated using Darcy’s law enhanced with a non-laminar flow term, assuming that it is similar to flow between parallel plates. The duration of flow in a weep is described by a flow-episode frequency factor which, by limiting the amount of water passed in each weep, effectively increases the number of weeps.

In the model, flowing fractures are created and the infiltrating water is divided among them until all the water is allocated. The weeps are then positioned at random, assuming that they are uniformly distributed within Yucca Mountain. The probability of a weep intersecting a container is a function of the geometry of the system. Containers that are contacted by weeps undergo corrosion, and if the duration of contact is sufficient, eventual failure and release of radionuclides. In the updated weeps model, container failure and waste mobilization are described using Lawrence Livermore’s YMIM source model.

Although the weeps model uses the physics of flow between parallel plates to describe flow in fractures, the weeps model is not a process model, per se. The weeps model calculates probabilities, based on the assumption that random events and situations can control when a weep flows and for how long. For a total-system calculation, the general physics of unsaturated flow in a fracture network might not be as important as presently unknowable factors—future weather patterns, future evapotranspiration, future topography, subsurface heterogeneity, etc. It is planned, however, to incorporate as much physics as possible in the future development of the weeps model.

As mentioned, in the weeps model no interaction is presently included between the tuff matrix and the water flow in the fractures. In the composite-porosity model, the other alternative conceptual model used in TSPA calculations, flow is allowed in both the matrix and the fractures.
and the flow is completely coupled. Hence, the weeps model is a bound for matrix-fracture interaction. But the weeps model is not a bound for repository performance—i.e., we cannot say that it represents either a best-case or worst-case scenario for releases from the repository. Although it was initially assumed that rapid flow in fractures might depict the worst-case scenario that a repository might experience with respect to groundwater flow, Gauthier et al. and TSPA-91 have shown that our intuition was faulty. The weeps model is simply a tool for investigating how a repository might perform if flow is limited to discrete, locally saturated zones through Yucca Mountain.

**IMPROVEMENTS**

**Varied weep sizes.** A major assumption made in TSPA-91 was that weep flow could be characterized using a single size for all the weeps. Thus, during a given realization, all containers contacted by weeps were contacted by the same amount of water for the same duration (the entire 10,000-year performance period). This abstraction was based on the parallel-plate-fracture approximation that shows flow increasing as a cubic function of the aperture. Thus, the largest weeps would pass a disproportionate amount of water and could be used to characterize the entire system. (It also allowed a repository-scale source term to be used, by simply reducing the size of the repository to the number of containers that were contacted by weeps.) Results of TSPA-91 proved to be sensitive to the size of the weeps, however, and indicated that the smaller the weeps, the larger the number of weeps, and the greater the releases, primarily because more containers are contacted. In TSPA-93, for each given realization, the updated weeps model produces a flow pattern based on a distribution of weep sizes. Because no data exist concerning weep sizes at Yucca Mountain, they are assumed to be directly related to fracture sizes.

**Weep size based on site fracture data.** To determine the aperture of a weep in TSPA-91, values were selected from a lognormal distribution with a minimum of 10 µm and a maximum of 1 mm, giving a mean of 214 µm. This distribution was arbitrary, justified only because it included the values for apertures of fractures typically seen at Yucca Mountain. The aperture for a weep probably cannot be characterized by observations of fracture aperture at a few discrete locations, however. The flow is likely to be constrained by constrictions that appear somewhere in the path. For TSPA-93, a method was devised for determining hydraulic aperture based on bulk-permeability measurements, which should have path constrictions implicitly included. From the site data, the fracture-aperture distributions for all geologic units exhibited a coefficient of variation close to 1, implying an exponential distribution. In TSPA-93, weep apertures were assumed to follow an exponential distribution. The mean of this distribution was chosen at random between a minimum of 100 µm and a maximum of 260 µm for each realization, giving a mean of the mean aperture of 180 µm. 180 µm is the mean value calculated for the TSw unit; the range of 100 to 260 µm includes the mean values calculated for most of the other geologic units.

**Flow-pattern changes caused by environmental effects.** In TSPA-91, weep flow was held constant for the 10,000-year duration of a single realization. We assumed that, for the next 10,000 years, the infiltration rate would continue as at present, and that there would be no significant changes in climate or topography at Yucca Mountain to cause weeps to change location. No data exist concerning changes in flow patterns at Yucca Mountain. The set of flowing fractures at tunnels in Rainier Mesa appears to be relatively constant on the timescale of years. It is reasonable to assume, however, that earthquakes, changes in topography, or changes in climate could change flow patterns. The updated weeps model allows abrupt changes in weep number, size, and location at either arbitrary times or times that coincide with climate changes. For lack of data, the new pattern is assigned without memory of previously flowing weeps. In TSPA-93, flow pattern changes were allowed only when the climate changed. The climate was specified to change from a dry climate (intended to represent a period between ice ages, such as the present climate) to a wet climate (intended to represent a pluvial period during an ice age) and back within every 100,000-year time period. We assumed that wet climates produce more infiltration than dry climates: during dry climates, infiltration rates averaged 0.5 mm/yr; during wet climates, 10 mm/yr. (For the weeps model, because of the postulate that flow is gravity-driven downward, it was assumed that all infiltrating water contributed to the groundwater flux through the repository; the fluxes used with the composite-porosity model were reduced.) In order to track these evolving conditions, the updated weeps model accounts for each container individually throughout a realization.

**Flow-pattern changes caused by repository heat generation.** Modeling suggests that repository-generated heat can inhibit groundwater flow in parts of a repository. In TSPA-91, hydrothermal effects caused by repository heat generation were modeled by a simple delay time that specified when conditions returned to ambient. In TSPA-93, thermal effects were parameterized according to the area encompassed by the boiling isotherm (to determine the containers that are protected from weep flow), and the volume encompassed by the boiling isotherm (to determine the amount of water that is displaced by the thermal pulse and can be added to groundwater flow). The boiling isotherm was assumed to correspond to a “dryout zone,” in which groundwater flow is inhibited. To incorporate the hydrothermal effects, the updated weeps model responds to
changes in the dryout zone. As the dryout zone expands, weeps that fall within that zone are eliminated. Water displaced by the dryout zone is added to the infiltrating water, and both these sources are used to create weeps that are either directed to parts of the repository that are not within the dry-out zone, or are shed altogether. The weeps that had been flowing outside the dryout zone continue unabated. As the dryout zone contracts, displacement of water ceases. The infiltrating water that had been flowing in areas outside the dryout zone is then redistributed: weeps are subtracted from some areas, and created in the areas newly unprotected by the contracting dryout zone. Flow returns to formerly dry areas of the repository coincident with the collapse of the dryout zone—i.e., no "extended-dry" period is recognized.

FLOW PREDICTIONS

Calculations were performed to investigate the differences in flow predicted by the original weeps model used in TSPA-91 and the updated model used in TSPA-93. To allow comparison with TSPA-91 results, the repository design used in the calculations was a 57 kW/acre thermal loading with thin-wall, vertical-borehole-emplaced, SCP-type containers.

Figure 2 shows the probability of calculating a given number of weeps using the original and updated weeps models. The calculations by the original weeps model used the TSPA-91 fracture-aperture distribution and a constant infiltration rate of 1 mm/yr. The calculations by the updated model used the TSPA-93 fracture-aperture distribution and included flow pattern changes induced by climate-change and hydrothermal effects. Separate calculations (not presented) showed that the difference in number of weeps caused by the change in aperture distribution is surprisingly insignificant, so the difference in the curves is primarily due to the effect of varied weep sizes and flow-pattern changes. Also, the original-model calculations were time independent (although they were intended to cover 10,000 years), but, because time is significant with respect to the discussion of flow-pattern changes, the updated-model calculations covered 1,000,000 years—encompassing a repository thermal pulse of several thousand years and approximately ten dry-climate/wet-climate cycles.

The original weeps model shows a wide spread in the cumulative distribution function (CDF) of the number of weeps generated. The median number of weeps predicted by the original weeps model is only several thousand, but because the original model restricts weeps to a single size in a given realization, when a very small aperture is sampled, billions of weeps are required to pass all the infiltrating water. The updated weeps model produces a much narrower distribution because a few large weeps are almost
always sampled in any given realization; subsequently, the large weeps pass a disproportionate amount of the inflow, and less water is available to generate small weeps. The median number of weeps for the updated model is approximately 20,000; however, the maximum is on the order of 2,000,000.

Also included in Figure 2 are results for the updated model with the flow-pattern changes excluded and included separately. Without any flow perturbation, the updated model predicts that very few weeps are generated—a median of about 300. (This value can be considered what the weeps model predicts as most likely for the present situation, bearing in mind that it is probably an overestimate because of the conservatism built in the model.) Inclusion of either repository-thermal effects or climate changes increases the number of weeps by approximately 2 orders of magnitude.

Figure 3 shows the probability a given number of weep-contacted containers calculated using several versions of the weeps model. The original weeps model predicts that somewhat over 20% of the time no containers are contacted by weeps; however, about 5% of the time, all of the containers are contacted. Between these two extremes, the CDF is approximately loguniform, with a median of about 20. The updated weeps model more closely predicts a lognormal CDF, with extremes of 100 and 10,000 contacted containers, and a median of slightly over 1000.

The sensitivity of the results to thermal effects and climate changes is similar to that shown in Figure 2. Without either flow perturbation, the model predicts that very few containers are ever contacted by weeps—typically only 2 contacts are predicted. Inclusion of either thermal effects or climate changes increases the number of contacts to several hundred. Climate change increases the number of contacts slightly more than thermal effects; however, as noted in TSPA-93, contacts when container temperatures are elevated cause the vast majority of container failures, and thus, the most significant total-system sensitivity is to thermal effects.

**RELEASE PREDICTIONS**

A major purpose of TSPA-93 was to offer performance-related guidance to Yucca Mountain Site Characterization Project (YMP) participants engaged in site-characterization and repository-design activities. Four different repository designs were investigated: (1) a base case 57-kW/acre repository with thin-wall, vertical-borehole-emplaced containers (similar to the repository investigated by TSPA-91); (2) a 114-kW/acre repository with vertical-borehole-emplaced containers; (3) a 57-kW/acre repository with multi-purpose, in-drift-emplaced containers; and (4) a 114-kW/acre repository with in-drift containers. For TSPA-
93, emplacement of some defective containers was assumed (twice as many defective vertical-borehole containers as defective in-drift containers were specified, on the premise that the double-walled in-drift containers are more reliable.) Calculations examined both nominal (undisturbed) and disturbed (human intrusion and volcanic-dike intrusion) conditions. Results were judged against two performance measures: the formerly applicable cumulative-release standard from the U.S. Environmental Protection Agency to allow comparison with TSPA-91, and the radiation dose from drinking water to allow comparison with a potential future dose regulation.

The complementary cumulative probability distributions (CCDFs) presented in Figure 4 show the performance of the four different potential repositories as measured by the EPA regulation. The probabilities are conditional because only aqueous releases calculated by the weeps model are included. The gaseous-releases CCDFs are similar. (Unlike the composite-porosity model, where normalized cumulative releases are dominated by gaseous releases, normalized gaseous releases predicted by the weeps model are approximately the same order of magnitude as aqueous releases.)

CCDF curves generated for all four repository configurations are within the EPA limits (i.e., none of the lines fall within the shaded region). However, the repositories with containers placed in-drift perform worse than the repositories with containers placed in vertical boreholes. A secondary effect is that the repositories with a high thermal loading perform worse than those with a lower thermal loading. The emplacement mode causes a difference in performance because the in-drift containers are a bigger target and are more likely to be hit by weeps. The higher thermal loading causes a difference in performance because more heat displaces a greater volume of water, which causes a greater number of weeps, and therefore, a greater number of containers contacted by weeps. These cumulative-release results are most sensitive to container corrosion, the weep-flow parameters (flux, flow-episode frequency, aperture), and radionuclide adsorption in the saturated zone. The gaseous cumulative releases are also sensitive to the number of defective containers.

Figure 4 also presents the results from the TSPA-91 weeps-model calculations. The TSPA-91 CCDF shows greater spread than the TSPA-93 curves, primarily because of the greater variance in number of weeps and number of containers contacted by weeps (Figures 2 and 3). The magnitude of releases is similar, however, for two reasons. First, despite apparently major differences, the phenomenological source term used in TSPA-93 produced container
failure times and release rates similar to the more subjective source term used in TSPA-91. Second, the weeps model contains an inherent trade-off between number of containers contacted by weeps and the amount of water carried by the weeps. When a large number of containers are hit, as happened often in the TSPA-91 calculations, the weeps are typically small, and less waste is dissolved. When only a few containers are hit, as happened often in TSPA-93, the weeps typically carry a large amount of water, and a large amount of waste is mobilized.

The predicted maximum radiation dose from drinking water over 1,000,000 years for all four analysis cases is shown in Figure 5. (A curve for TSPA-91 results is not included because similar doses were not calculated in TSPA-91.) As with Figure 4, worse performance is predicted for large containers and a hot repository. The figure shows that the median dose is in the neighborhood of several millirem per year; in the extreme case, doses exceed several rem per year. The dose calculations are most sensitive to the dilution in the saturated zone and the weep-flow parameters.

**CONCLUSIONS**

The weeps model has been modified to better represent possible flow conditions at Yucca Mountain. Improvements include allowing weeps to be of different sizes and allowing their distribution in space to change with time in response to environmental influences or repository heat generation. Calculations with the updated weeps model lead to some general conclusions concerning the impact of weep flow on a repository. First, when weeps are of varied size, on average fewer weeps result, and fewer containers are contacted by weeps at any given time. This situation occurs primarily because a set of weep sizes usually includes a few big weeps, and big weeps carry a disproportionate amount of water. Second, when weeps change position in time, more containers are eventually contacted by weeps, but on average for a lesser duration. If the container lifetime is greater than the duration of contact, which could be the case especially when containers are relatively cool, then releases do not occur.

Results of TSPA calculations using the updated weeps model indicate that performance is enhanced when container cross-sectional area is minimized and, to a lesser extent, when large-scale perturbations to the flow system caused by repository heat generation are minimized. Doses from a repository are predicted to be non-negligible, although significantly less than those predicted by the composite-porosity model.10

Based on these results (and even more on the results of the composite-porosity model), meeting a dose standard at Yucca Mountain could be more problematic than meeting a cumulative release standard. Key performance issues might
no longer be time related—e.g., duration of thermally induced dryout, or radionuclide travel time through the Calico Hills stratum—when dealing with potential radiation doses hundreds of thousands of years in the future. Rather, the key issues could be the radionuclide release rates from a repository and the dilution afforded by the environment. The weeps model predicts lower release rates and lower doses than does the composite-porosity model, primarily because of the protection that probability affords against the relatively rare event of a container being contacted by a weep. This finding should not generate complacency, however. This finding should represent a challenge to the YMP site characterization effort to determine the existence and extent, both spatially and temporally, of weep flow at Yucca Mountain.

REFERENCES


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