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ESTIMATING THE CONSEQUENCES OF SIGNIFICANT FRACTURE FLOW AT YUCCA MOUNTAIN

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ABSTRACT

A simple model is proposed for investigating the possibility of significant fracture flow at Yucca Mountain, Nevada. The model allows an estimate of the number of flowing fractures at Yucca Mountain based on the size of the fractures and the yearly volume of infiltrating water. Given the number of flowing fractures, the number of waste containers they contact is estimated by a geometric argument. Preliminary results indicate that the *larger* the flowing fractures, the *lower* the releases of radionuclides. Also, even with significant fracture flow, releases could be well below the limits set by the Environmental Protection Agency.

INTRODUCTION

The partially saturated tuffs at Yucca Mountain, Nevada, are a site for a potential repository for high-level radioactive waste. Groundwater flow through fractures in the unsaturated zone could have a negative effect on repository performance. This paper presents an initial estimate of the impact of significant fracture flow on a repository, and offers a relationship between the size of the flowing fractures and the releases of radionuclides. In the analysis, an attempt is made to bias the assumptions to produce conservative results, i.e., to overestimate the releases of radionuclides. The fracture-flow model included in the Total-System Analyzer (TSA)[1] is based on the described analysis.

FRACTURE FLOW AT YUCCA MOUNTAIN

Significant fracture flow in the unsaturated zone implies predominantly gravity-driven flow through fractures with minimal interaction with the matrix. Figure 1 illustrates a conceptual model of fracture flow at Yucca Mountain.

[a] This work was performed under the auspices of the U.S. Department of Energy, Office of Civilian Radioactive Waste Management, Yucca Mountain Site Characterization Project, under contract DE-AC04-76DP00789.

Supporting evidence for fracture flow at Yucca Mountain is circumstantial. Secondary mineralization on the walls of fractures has been reported at Yucca Mountain,[2] and these deposits could indicate prior fracture flow. Continuous water seepage from a fracture occurs at G-tunnel, located to the north of Yucca Mountain at Rainier Mesa, in unsaturated welded tuff similar to the tuffs at Yucca Mountain (F. Hansen, personal communication). A rate of infiltration (between 0.5 and 4.5 mm/yr)[3] has been suggested that is greater than the saturated conductivity of much of the matrix in the welded tuffs (generally less than 1 mm/yr).[4] If this amount of water is percolating through the tuff matrix, the matrix should be saturated; however, in-situ matrix saturations reported by the Yucca Mountain Reference Information Base, Version 4 (RIB 1.4.2), are approximately 60 percent. Radioactive ^{36}Cl has been reported in the Topopah Spring unit at drill hole USW UZ-6.[5] ^{36}Cl is a remnant of the atmospheric testing of nuclear weapons that took place within the last 50 years, and its presence deep inside Yucca Mountain suggests groundwater travel times much shorter than should occur when flow is predominantly through the matrix. And finally, ambiguous evidence for fracture flow has been reported at USW UZ-1.[6] Water contaminated with drilling fluids presumably from USW G-1 was found at the bottom of dry-drilled USW UZ-1, suggesting that the fluids had flowed the 300-m distance through the fractures. But no evidence of weeping fractures was seen through a camera lowered into USW UZ-1.

CONDITIONS AND FEATURES CONTRIBUTING TO FRACTURE FLOW

According to our current understanding of flow in the unsaturated zone, significant fracture flow at Yucca Mountain is problematic. The layer of alluvium covering the mountain, and the tuff matrix (especially the highly conductive, fracture-sparse nonwelded tuffs) should damp fracture flow like a sponge.[7] And once flow is in the matrix, positive pressure heads would be required to force the water back into the fractures—pressure heads that have not been observed in the unsaturated zone at Yucca Mountain.[3,6] For fracture flow to occur, specific conditions and features must exist to initiate flow in fractures, then sustain the flow.

Conditions for initiating fracture flow must be such that either water is channeled directly into fractures, water locally saturates the porous medium and forces flow in fractures, or the matrix is isolated from the flow. Surface conditions at Yucca Mountain that could contribute to initiating flow in fractures are as follows: annual cycles of infiltration; spatial variation in precipitation causing large localized pulses of water; runoff through washes causing large, localized pulses; and, direct precipitation on, or runoff over, outcroppings of fractured tuffs. Subsurface features within Yucca Mountain that could contribute to the initiation of fracture flow in underlying strata include heterogeneities; buried topographical features (e.g., paleowashes); undulations in nonwelded geologic units (causing water to pool above fractured, welded geologic units); dip of the geologic units and the conductivity contrast between geologic units (causing lateral diversion of flow that eventually reaches locally saturated conditions); and the pinching out of geologic units that carry significant flow.

In order to sustain flow in fractures, exchange of water between the matrix and fractures—"coupling" or "communication" between matrix and fractures—must be limited. Conditions that reduce matrix/fracture coupling and work to retain water in fractures include the following: short time scale of flow (e.g., flow in pulses, with large amounts of water passing through fractures with large apertures); low hydraulic conductivities in the matrix; hysteretic effects that slow the wetting of the matrix; coatings on the fracture walls;[9] and, capillary barriers (e.g., dry fractures) that restrict lateral movement of water by imbibition into the matrix (resulting in a localized saturated zone around the flowing fracture).

Many of the above conditions and features are known to exist at Yucca Mountain. Whether these conditions and features actually contribute to fracture flow at Yucca Mountain is speculative.

QUANTIFICATION OF FRACTURE FLOW

A strategy for quantifying fracture flow can be founded on the fact that a finite volume of water infiltrates Yucca Mountain. By determining the amount of water that a single fracture can pass, the number of fractures necessary to handle the influx can be estimated. Knowing the number of fractures, we can estimate the number of waste containers that are subjected to fracture flow, and the subsequent releases.

A reasonable limit on the volume of infiltrating water (V_{in}) that could affect a repository at Yucca Mountain, is the product of the estimated maximum rate of infiltration (q = 4.5 mm/yr)[3] and the area of the potential repository ($A_{rep} = 5.61 \times 10^6$ m^2), or 25,200 m^3/yr.

The hydraulic conductivity of an ideal fracture (K_f) can be calculated using a parallel-plate model:

$$K_f = \frac{\rho g}{\mu}\frac{b^2}{12} ,$$

where b is the fracture aperture, and $\rho g/\mu$ is the product of water density (ρ = 1000 kg/m^3) and gravity (g = 9.76×10^{15} m/yr^2) divided by the dynamic water viscosity ($\mu = 3.16 \times 10^4$ kg/m-yr at 20° centigrade), and is equal to 3.09×10^{14} m^{-1}yr^{-1} in the units being used.[10]

The maximum rate of flow through a single fracture can be found using Darcy's law, elaborated to account for nonlaminar flow:

$$q_f + 0.55\sqrt{\frac{\rho}{\mu g}K_f}\; q_f^2 = K_f\frac{\partial h}{\partial l} \qquad \Longrightarrow$$

$$q_f = \frac{Q_f}{A_f} = \frac{-1 + \sqrt{1 + 2.2K_f\sqrt{\frac{\rho}{\mu g}K_f}\;\frac{\partial h}{\partial l}}}{1.1\sqrt{\frac{\rho}{\mu g}K_f}} ,$$

where q_f is the flux through the fracture, Q_f is the rate of flow through the fracture (the quantity of interest), A_f is the area of the fracture perpendicular to flow, and $\partial h/\partial l$ is the hydraulic gradient.[11] We assume the hydraulic gradient is one—water flow is dominated by gravity, and not affected by capillary forces or by the weight of the water ponded above.

The number of flowing fractures (N_{weeps}) and the water flow rate through a single fracture (V_{weep}) can now be calculated as follows:

$$N_{weeps} = \frac{V_{in}}{Q_f} \times F \,, \qquad V_{weep} = \frac{V_{in}}{N_{weeps}} = \frac{Q_f}{F} \,,$$

where F is the weep-episode factor ($F = 12$). The periodicity of an episode is assumed to be one year, based on the generalization that most infiltration occurs during the winter or early spring, when evapotranspiration is minimal, and snowmelt provides infiltration with minimal runoff.[12] The duration of the flow is then a fraction of a year; one month is assumed for lack of specific data.

Consider, for example, flow through fractures with apertures of 100 μm and horizontal lengths of 1 m ($A_f = 10^{-4}$ m^2). An aperture of 100 μm is large enough to allow fracture flow with limited matrix/fracture coupling[13] and is also close to the 78-μm estimate of the average effective fracture aperture for the unsaturated geologic units at Yucca Mountain, calculated from well-test data.[14] Observation (C. Rautman, personal communication) and geometric considerations suggest that a horizonal length of 1 m is reasonable. It is unlikely that all the water from a fracture that has a horizontal length of 10 m would contact a waste container with a cross-sectional area of 0.66 meter. In any event, a flowing fracture with a horizontal length of 10 m can be considered to be ten 1-m fractures.

For this example fracture, the flow rate (Q_f) is calculated to be 23.1 m^3/yr. Thus, to pass 25,200 m^3/yr requires 1090 fractures of this size. If we assume that fracture flow is episodic and that fractures only flow for one month out of the year, then approximately 13,100 100-μm fractures (1090 × 12) are required to pass the volume of water that could infiltrate above the potential repository area. The water flow volume (V_{weep}) through one of these fractures averages 1.92 m^3/yr.

It is interesting to note that, because of the nonlinearity in the above equations, a single 5-mm-by-1-m fracture (perhaps part of a fault) could pass the entire amount of water that infiltrates Yucca Mountain in one year.

Major Assumptions for Quantification of Fracture Flow

1) Significant fracture flow exists at Yucca Mountain; this assumption requires that continuous fracture pathways exist (i.e., flowing fractures are connected), and that there is little or no matrix/fracture coupling in the flowing fractures. Additionally, we assume that all water entering Yucca Mountain proceeds to the water table via fracture flow.

2) The flowing fractures with the largest flow apertures can be used to characterize all flowing fractures

at Yucca Mountain. We define the "flow aperture" of a fracture as the aperture required to pass the water flowing in the fracture as if the fracture were flowing at capacity. The flow aperture varies with the cube of the amount of water carried by the fracture. Therefore, the fractures with the largest flow apertures will dominate the flow and can be considered as representative of the flow system.

3) The rate of groundwater infiltration into Yucca Mountain averages 4.5 mm/yr or less for 10,000 years.

4) Flowing fractures are uniformly distributed in Yucca Mountain. With this assumption, the number of waste containers in contact with flowing fractures is probably maximized. If flowing fractures were concentrated in only a few areas, only containers in those areas could be contacted.

5) Weeps always flow through the same fractures; flow does not switch from one fracture or set of fractures to another.

6) The disturbed zone surrounding the repository drifts has no appreciable effect on fracture flow.

QUANTIFICATION OF RELEASES

The number of waste containers subjected to flow from fractures can be estimated by a geometric argument, as illustrated in Figure 2.

The area in which a flowing fracture affects a waste container ($A_{contact}$) is estimated by the size of the fracture and the exposed area of a waste container. The probability of a given flowing fracture contacting a waste container ($P_{contact}$) is then the product of the total number of waste containers in the potential repository and the ratio of the area of contact and the area of the potential repository. The number of flowing fractures contacting containers ($N_{contact}$) is assumed to follow the binomial distribution. The equations are as follows:

$$A_{contact} = w_f d_{can} + \pi(\frac{1}{2} d_{can})^2 \ ,$$

$$P_{contact} = N_{cans} \frac{A_{contact}}{A_{rep}} \ ,$$

$$N_{contact} = N_{weeps} P_{contact} \ ,$$

$$\sigma_{contact} = \sqrt{N_{weeps} P_{contact} (1 - P_{contact})} \ ,$$

where w_f is the horizontal length of a flowing fracture, d_{can} is the diameter of a container (d_{can} = 0.66 m), N_{cans} is the total number of containers in the potential repository (N_{cans} = 35,000), and $\sigma_{contact}$ is the standard deviation of $N_{contact}$.

As shown below, maximizing the number of containers contacted by flowing fractures maximizes releases. We therefore assume that no two flowing fractures contact the same container—i.e., that the number of flowing fractures contacting containers is equal to the number of containers contacted by flowing fractures ($N_{contact}$).

Figure 3 presents the relationship between the size of the flowing fractures and the number of waste containers contacted. In general, larger flow apertures imply that fewer fractures are flowing; fewer flowing fractures result in a lower probability that containers will be contacted. At the extremes, if the flow aperture of the flowing fractures is on the order of 1000 μm (1 mm), only one container can be expected to be contacted. If the flow aperture is 12 μm, all 35,000 containers would probably be contacted. As indicated by the one-standard-deviation bound (the dashed lines), there is little uncertainty in these numbers. For our 100-μm-by-1-m fractures, the expected number of flowing fractures that contact containers is 82, with a standard deviation of 9.

To calculate the releases from a container in contact with a flowing fracture, the "alteration-rate" model is used. This model holds that the uranium matrix undergoes an oxidation alteration, and volatile elements (especially carbon, technetium, and iodine) are released from the waste form faster than the uranium fuel matrix dissolves; nonvolatile elements are leached congruently with the fuel matrix.[15] (We are ignoring the fact that some elements, e.g., neptunium, are less soluble than uranium.) Because the alteration rate of the uranium fuel matrix could be short compared with the 10,000-yr time span of regulatory interest for a high-level radioactive waste repository, we assume that the volatile elements are immediately released from a waste form contacted by a flowing fracture. For the nonvolatile elements, releases are a function of the total mass of dissolved waste (M_{dis}), which is calculated by first determining the time scale for dissolution of a waste form (t_{dis}), as follows:

$$t_{dis} = \frac{M_U}{\max(1, N_{contact}/N_{cans})V_{weep}S_U} ,$$

$$M_{dis} = \min(1, \frac{t_{reg}}{t_{dis}})\min(N_{contact}, N_{cans})M_{can} ,$$

where M_U is the mass of the uranium fuel matrix in a container (the major constituent of the waste, M_U = 8400 moles, or approximately 2 metric tons in the units being used), S_U is the solubility of uranium (an upper-limit estimate of which is S_U = 0.2 mol/m^3, or 4.76 $\times$ 10^{-5} metric tons/m^3 in the units being used),[16] t_{reg} is the time span of regulatory interest (t_{reg} = 10,000 yr), and M_{can} is the mass of waste in a container (M_{can} = 2 metric tons of heavy metal—MTHM). Note that M_U must be approximately equal to M_{can} for these equations to hold. The floor function, $\max(1, N_{contact}/N_{cans})$, enforces the following condition: if more than one flowing fracture contacts a container, then the average amount of water from the average number of fractures contacts the container; otherwise, all the water from one fracture contacts the container. The ceiling function, $\min(1, t_{reg}/t_{dis})$, limits the amount of waste dissolved from a single container to the contents of one container. And the ceiling function, $\min(N_{contact}, N_{cans})$, limits the number of waste containers that can be dissolved to the number of containers.

Our example 100-μm-by-1-m fractures, each passing 1.92 m^3/yr of water, would dissolve an entire container's 2 metric tons of heavy metal (MTHM) in 21,900 yr. In 10,000 yr, 75 MTHM of waste would be dissolved out of the 82 containers (holding 164 MTHM) contacted by flowing fractures. Therefore, 46 percent (75/164) of the nonvolatile radionuclides would be released from the 82 containers. All of the volatile elements would be released from the 82 containers.

A very simple transport model is used to determine releases to the accessible environment. Gas-phase radionuclides—only ^{14}C in this analysis—are assumed to be transported instantly to the accessible environment. Water-soluble radionuclides are assumed to move through the unsaturated zone and the saturated zone to reach the accessible environment. Transport through the unsaturated zone is assumed to be instantaneous. Transport through the saturated zone is calculated by the product of the minimum groundwater travel time through the saturated zone ($GWTT_{SZ}$) and the retardation factor for each radionuclide. All weakly sorbing radionuclides—i.e., radionuclides with retardations low enough to allow them to move 5 kilometers in 10,000 years—that are released from a waste container are assumed to be released at the accessible environment.

Estimates of $GWTT_{SZ}$ are found in a number of sources[12,17,18] and can range from hundreds to tens of thousands of years. For conservatism, the $GWTT_{SZ}$ used in this paper is taken to be 50 yr, implying that any radionuclides with retardations less than 200 could be released. Only 11 important radionuclides are believed to have retardations in welded tuffs of less than 200 (Table 1).[16]

Once the radionuclides that can reach the accessible environment are known, the following equations are used to quantify the releases of each radionuclide (C_{rel}) and the Environmental Protection Agency limits (EPA_{sum}) for the potential repository:

$$C_{rel,i} = \begin{cases} M_{can} N_{contact} C_{inv,i} & \text{[volatile elements]} \\ M_{dis} C_{inv,i} & \text{[nonvolatile elements]} \end{cases}$$

$$EPA_{sum} = \sum_i \frac{C_{rel,i}}{C_{limit,i}} ,$$

where i is the index of one of the list of radionuclides that can reach the accessible environment, $C_{inv,i}$ is the maximum inventory (in 10,000 yr) of radionuclide i (Ci/MTHM), and $C_{limit,i}$ is the EPA limit for radionuclide i (Ci).

Table 1 presents the 11 radionuclides, their maximum inventories, their EPA limits, and their estimated releases for the example 100-μm-by-1-m fractures. The EPA sum for this case is 0.079—well below the EPA regulatory limit of 1. In other words, if flow at Yucca Mountain is predominantly episodic through 100-μm fractures, releases can be expected to be less than the regulatory limit. (Of course, releases below the limit for this single scenario do not imply regulatory acceptance.)

Major Assumptions for Quantification of Releases

1) Waste containers are vertically emplaced, and the waste containers, like flowing fractures, are uniformly distributed throughout the repository horizon.

2) Only waste containers contacted by weeps fail, and they fail immediately. There are several corollaries to this assumption. First, the thermal output of the potential repository does not dry the fractures. Second, water from a flowing fracture begins to dissolve waste upon contact with the container. Third, containers not contacted by weeps do not release radionuclides; in particular, they do not release ^{14}C as a gas.

3) The "alteration-rate" model represents the radionuclide source. A competing model—the "congruent-leach-only" model—holds that the release of all radionuclides occurs at a rate proportional to the dissolution of the uranium fuel matrix. Releases to the accessible environment are sensitive to the choice of the source model—the releases calculated with the alteration-rate model can be over two orders of magnitude greater than those calculated with the congruent-leach-only model (below). Although evidence exists supporting the alteration-rate model, the evidence is not conclusive, and releases may be constrained by other factors. Past performance-assessment analyses[14,20] have used the congruent-leach-only model.

4) Dissolved waste is transported instantaneously through the unsaturated zone; i.e., radionuclide transport time in the unsaturated zone is negligible, and radionuclides do not interact with the tuffs in the unsaturated zone.

5) Matrix/fracture interaction does take place in the saturated zone. Matrix diffusion[21] of radionuclides occurs in the saturated zone; i.e., contaminants can diffuse from water in the fractures and mix with water in the tuff matrix. Sorption of radionuclides onto tuffs occurs in the saturated zone, and sorption ratios—retardations—are as given by DOE.[16]

6) Release mechanisms involving colloids are negligible.

RELEASES VERSUS FRACTURE SIZE

Figure 4 presents the relationship between the flow aperture of the major fractures controlling weep flow and the releases of radionuclides to the accessible environment. In general, the larger the flow aperture, the lower the releases.

Releases shown in Figure 4 are calculated using both the alteration-rate source and the congruent-leach-only source. Both source terms produce the same releases for flow apertures greater than 135 μm. At these large apertures, enough water is flowing to dissolve an entire waste form in 10,000 yr; therefore, all the volatile and nonvolatile radionuclides in a container are released in both cases.

At flow apertures less than 135 μm, releases resulting from the congruent-leach-only source are constant. For flow apertures smaller than 135 μm, the number of flowing fractures and the number of contacted containers increases; however, the amount of water flowing through each fracture decreases and only part of the waste form dissolves in 10,000 yr. The total amount of water contacting the total amount of waste remains constant, and the net effect is that the releases remain constant.

At flow apertures less than 135 μm, the releases calculated with an alteration-rate source continue to increase, because the number of containers contacted by flowing fractures continues to increase, and therefore, more volatile radionuclides are being released. Initially, the rate of increase is slower, as the curve adjusts to the now constant releases of nonvolatile radionuclides. Releases resulting from the alteration-rate source continue to increase until flow apertures decrease to approximately 12 μm. At flow apertures of 12 μm, all 35,000 containers in the potential repository are contacted. Although little water is flowing in the fractures (approximately 0.0037 m^3/yr), the alteration-rate model allows all the volatile radionuclides to be released from every container. The releases are constant below 12 μm because the number of containers is fixed.

CONCLUSIONS

The consequences of significant fracture flow on a potential repository at Yucca Mountain are primarily a function of the number of containers that are contacted by flowing fractures. In general, the fewer the number of flowing fractures, the fewer containers are contacted, and the lower the releases. This observation holds true even (or especially) if the flowing fractures are very large and carry a large volume of water.

Using a simplified model with many conservative assumptions, the consequences of significant fracture flow at Yucca Mountain can be estimated. With an alteration-rate model for the source term, maximum EPA sum is achieved at extremely small flow apertures, and is calculated to be approximately 17. For conditions most likely to exist at Yucca Mountain—both in terms of matrix/fracture coupling and measured fracture apertures—the EPA sum could be less than 0.2. With a congruent-leach-only model, the maximum EPA sum is reached at medium to small flow apertures, and is calculated to be approximately 0.06.

The model presented in this paper forms the basis for a fracture-flow model implemented in the Total-System Analyzer (TSA). A calculation performed by the TSA (described by Wilson[22] elsewhere in this *Proceedings*) uses probability distributions for model parameters along with the alteration-rate source. The calculation produces lower releases than the maximum EPA sum presented here.

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TABLE 1. Radionuclides[a] that can be transported to the accessible environment within 10,000 years given a ground-water travel time of 50 years (retardations less than 200). Releases are calculated using the alteration-rate source for 25,200 m^3/yr of water (4.5 mm/yr) infiltrating through 100-μm-by-1-m fractures and contacting 82 containers.

NUCLIDE	RETARDATION[b]	INVENTORY[c] (Ci/MTHM)	RELEASES[d] (Ci)	EPA LIMIT[e] (Ci)	EPA RATIO[f]
^{14}C	1	1.5	250	7000	0.035
^{99}Tc	8	12	2000	700,000	0.0028
^{129}I	1	0.030	4.9	7000	0.0007
^{210}Pb	120	0.12	9.0	70,000	0.0001
^{232}U	27	0.025	1.9	7000	0.0003
^{233}U	27	0.046	3.5	7000	0.0005
^{234}U	27	1.9	140	7000	0.020
^{235}U	27	0.020	1.5	7000	0.0002
^{236}U	27	0.33	25	7000	0.0035
^{238}U	27	0.32	24	7000	0.0034
^{237}Np	160	1.1	83	7000	0.012
				EPA SUM[g]	0.079

[a]Radionuclides with inventory EPA ratios greater than 0.02, and half-lives greater than 20 years.
[b]Retardations in welded tuff.[16]
[c]Estimated maximum inventory in 10,000 years, based on 60 percent PWR spent fuel and 40 percent BWR spent fuel.[19]
[d]Product of the inventory of the radionuclide and the total amount of dissolved waste.
[e]Assuming 70,000 MTHM in the repository.
[f]Calculated as the ratio of the radionuclide release to the radionuclide EPA limit.
[g]Sum of the EPA ratios.

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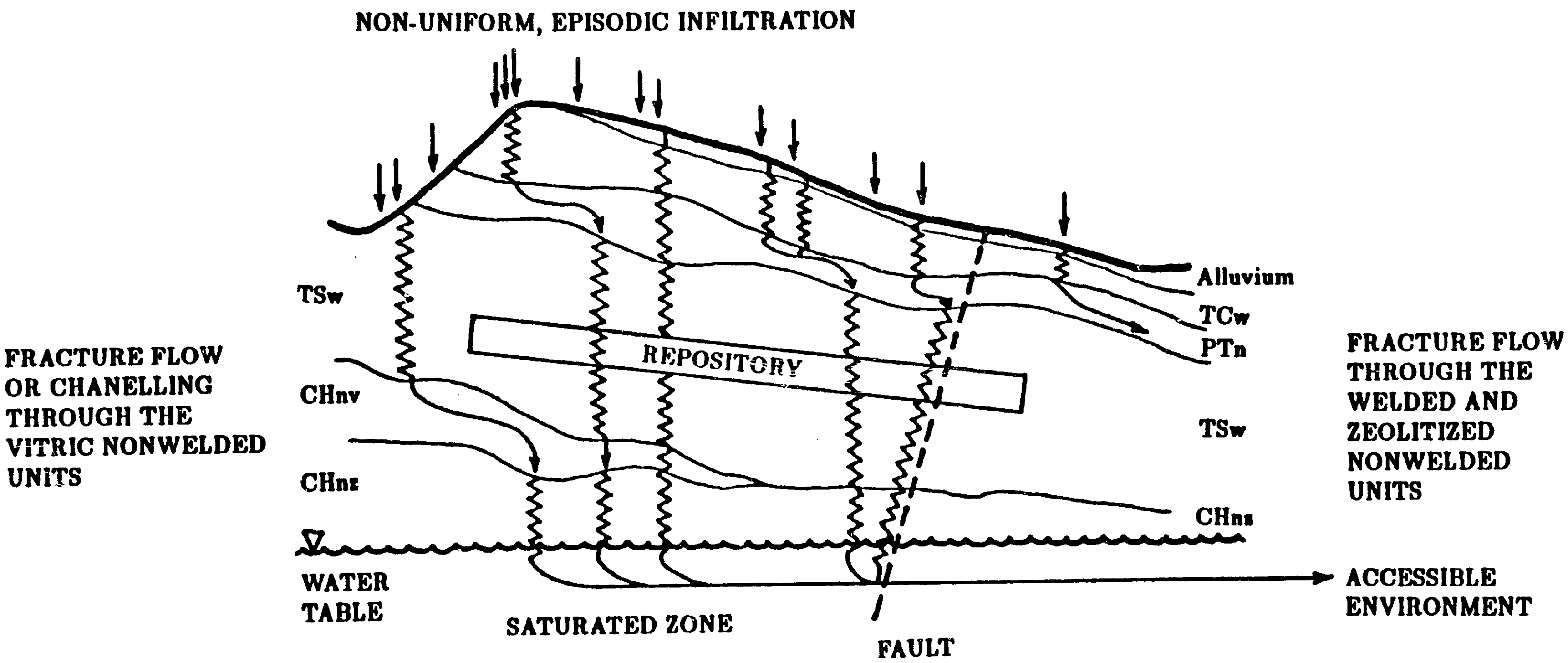

Figure 1. Overview of fracture flow (weeps) at Yucca Mountain.

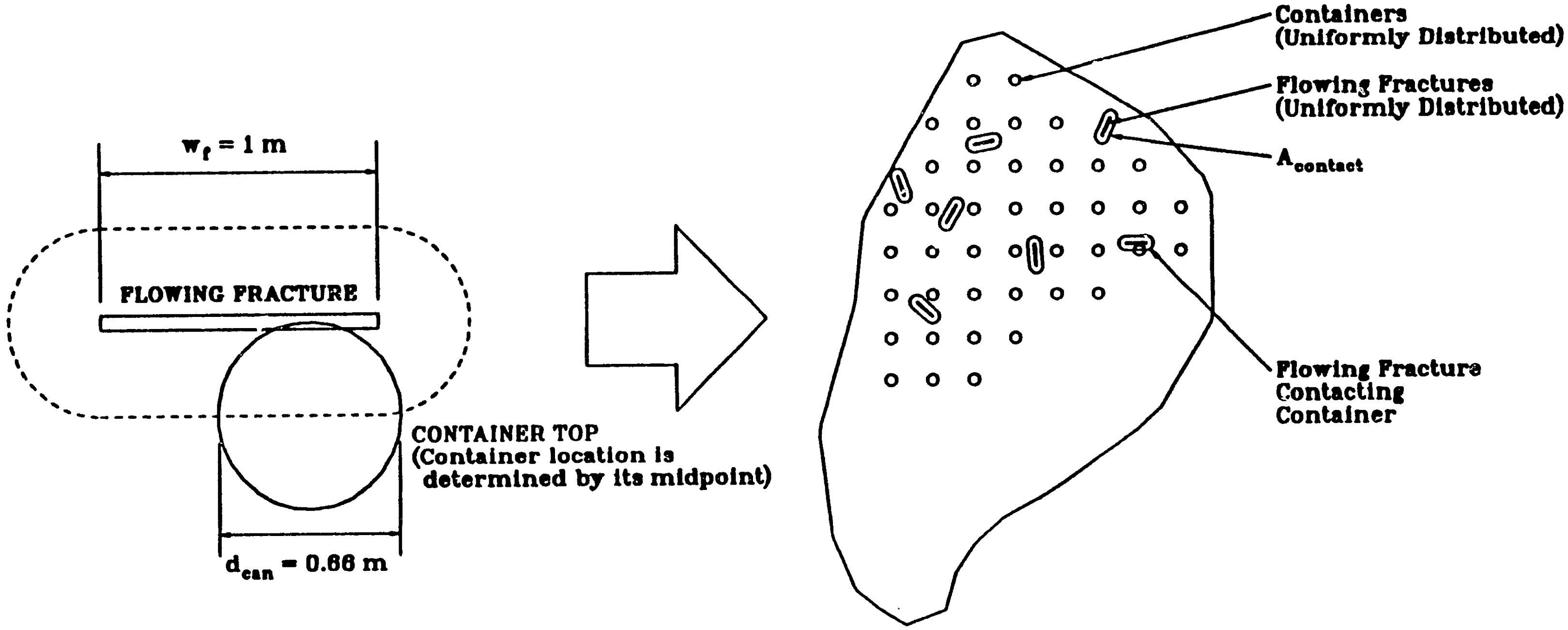

Figure 2. Geometric considerations in calculating the number of containers contacted by flowing fractures.

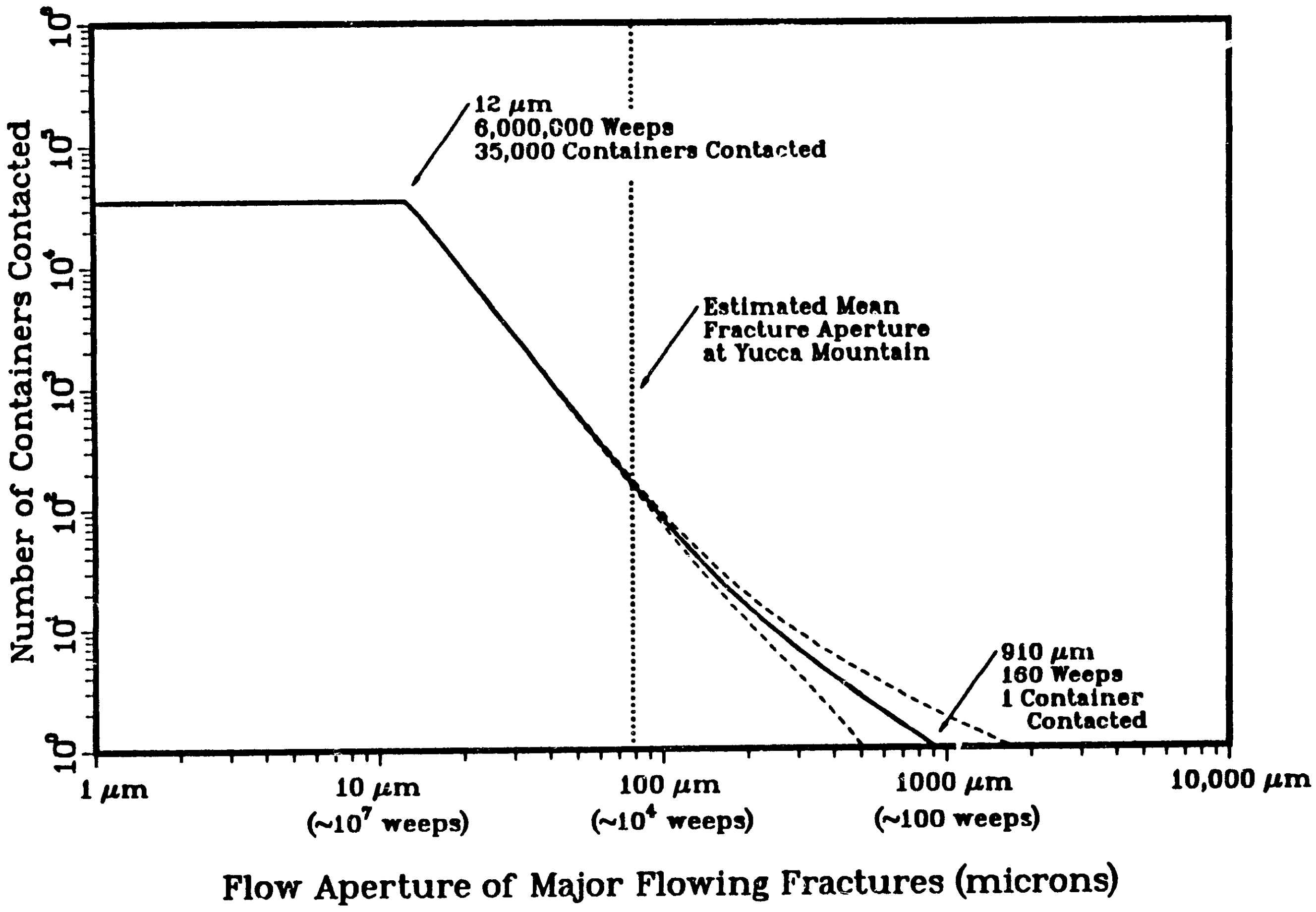

Figure 3. Relationship between the flow aperture of the major flowing fractures, the number of flowing fractures, and the number of waste containers contacted. The dashed lines represent plus or minus one standard deviation.

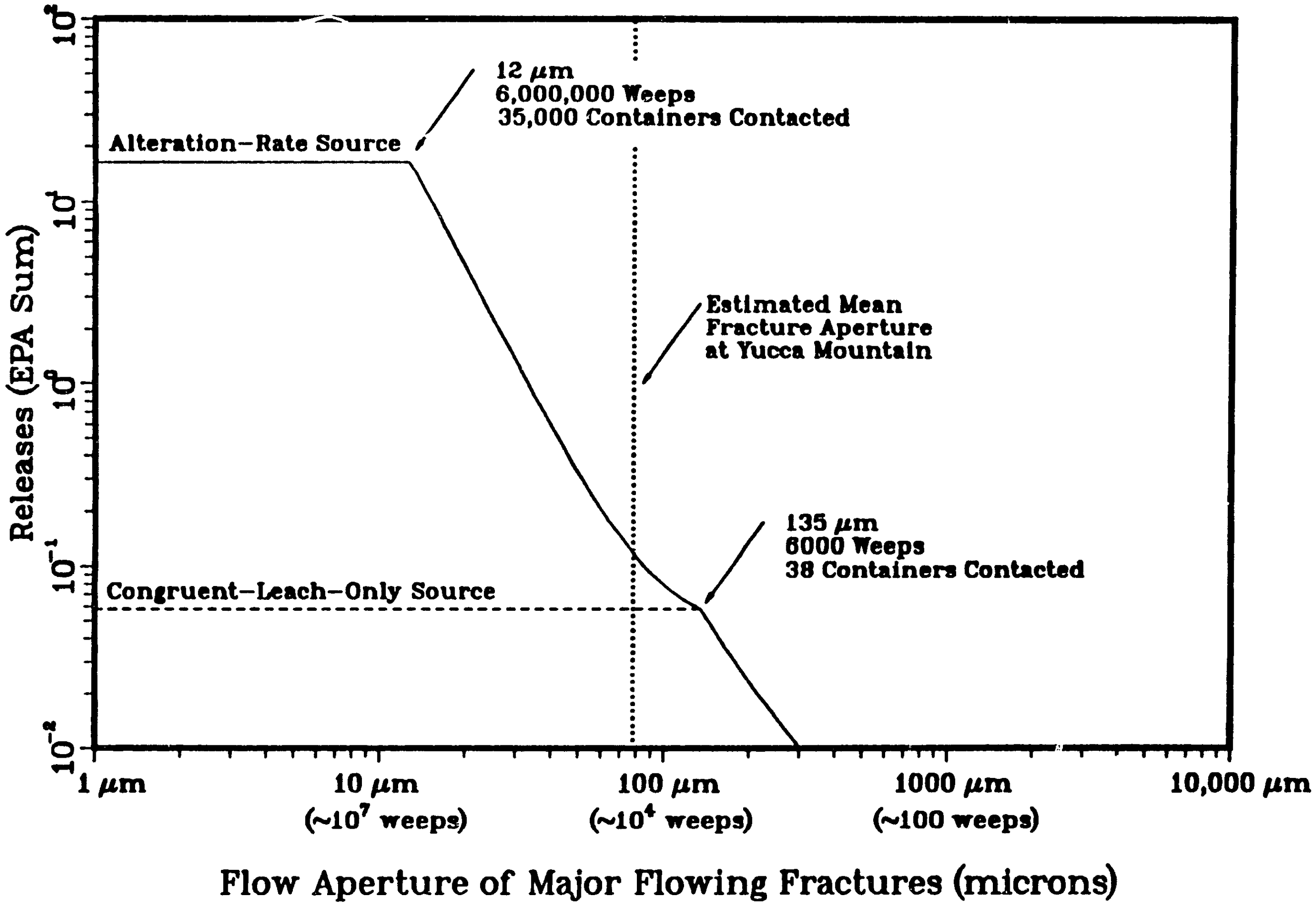

Figure 4. Relationship between the flow aperture of the major flowing fractures and the resulting releases from the potential repository.

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