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Date: September 27, 2004
Refer To: ER2004-0552

MDA H Focus Group Members

SUBJECT: FRACTURE FLOW FOR MDA H

Dear MDA H focus group member:

I am enclosing the study on fracture flow for Material Disposal Area (MDA) H. The study, requested by the independent peer reviewer, Mr. George Rice, demonstrated that under the conditions modeled, contaminants are transported faster, but in lesser amounts, through fractures in rock than through rock matrix. Although transport through the upper, fractured tuff units is faster, contaminants do not break through into the regional aquifer within the 1000-yr evaluation period. Thus, the results of the alternate analysis are the same as those of the baseline risk assessment in terms of groundwater-pathway risk.

Please review the study and if you have any questions, please call me at (505) 667-9551 or johnhopkins@lanl.gov. Thank you again for your interest and participation in the analysis of MDA H.

Sincerely,

John Hopkins
Project Team Leader for Material Disposal Area H

JH/jr

Enclosure: MDA H Fracture Flow Study

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September 2004
ER2004-0395

An Alternate Groundwater-Pathway Risk Assessment for Material Disposal Area H: Fracture-Facilitated Contaminant Transport

Los Alamos
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EST. 1943

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Prepared by Diana Hollis, Kay Birdsell, and John Hopkins, Los Alamos National Laboratory

Produced by Risk Reduction and Environmental Stewardship–Remediation Services, Los Alamos National Laboratory

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1.0 INTRODUCTION AND BACKGROUND

This document describes an alternate groundwater-pathway transport model and presents the results of the assessment that Los Alamos National Laboratory (LANL or the Laboratory) conducted to address stakeholder and New Mexico Environment Department (NMED) concerns about the potential transport of hazardous and/or radiological constituents in waste disposed of at Material Disposal Area (MDA) H to the regional water supply aquifer through fractures beneath the site. This concern was raised by stakeholders and NMED after they reviewed the baseline risk assessment conducted as part of the corrective measures study (CMS) for MDA H (LANL 2003, 76039). The baseline risk assessment evaluated the potential for contaminants in waste disposed of in unlined vertical shafts at the former disposal site to be dissolved and transported in water that slowly but steadily flows through the disposal shafts and the underlying bedrock. The groundwater-pathway portion of the MDA H baseline risk assessment evaluated contaminant transport to groundwater according to a conceptual model of matrix-dominated flow through the unsaturated tuff layers beneath disposal shafts and fracture-dominated flow through the basalt layer beneath the tuff. The CMS also evaluated alternative remedies to mitigate the potential release and transport processes and pathways identified in the baseline risk assessment.

The conceptual model presented in the MDA H CMS report is the most appropriate because it is based on actual site conditions, including geology, hydrology, and solubility of the wastes at MDA H. This document describes the alternate conceptual model of fracture-facilitated transport and discusses the risk related to this transport to determine whether the resulting risk is different from that calculated using the original conceptual model. While matrix flow is understood to dominate the movement of groundwater in nonwelded to moderately welded tuffs under unsaturated conditions, fracture flow may occur in tuff under saturated conditions. Saturated conditions occur infrequently within the mesas across the Pajarito Plateau, and fracture flow has been observed under saturated conditions in the more welded units of the Tshirege Member of the Bandelier Tuff. This assessment for MDA H examines a conceptual model where fractures provide an explicit pathway for contaminants to be transported through bedrock toward a drinking water source. This conceptual (and computational) model is consistent with the current state of knowledge gained from theoretical, experimental, and field studies of local fractured rock geology and of hydrology.

This analysis demonstrates that under the conservative conditions modeled, contaminants are transported faster, but in lesser amounts, through fractures in rock than through rock matrix. Although transport through the upper, fractured tuff units is faster, contaminants do not break through into the regional aquifer within the 1000-yr evaluation period. Thus, the results of the alternate analysis are the same as those of the baseline risk assessment in terms of groundwater-pathway risk.

2.0 SITE CONDITIONS RELATED TO FRACTURE FLOW

To understand the conceptual model discussed here, it is useful to understand how certain physical features and groundwater flow processes vary among and within the rock layers at MDA H, located at Technical Area (TA-) 54 on the eastern end of the Pajarito Plateau.

2.1 Geology

The Laboratory is located on the Pajarito Plateau, a dissected volcanic apron extending eastward from the Jemez Mountains. The plateau consists of long, narrow mesas separated by canyons cut by ephemeral streams. The plateau ranges in elevation from approximately 7800 ft on the flanks of the Jemez Mountain front to 6200 ft at its eastern termination at the Rio Grande.

Like most Laboratory facilities, MDA H is located on a mesa (Mesita del Buey) formed as an erosional remnant of the Bandelier Tuff. The Bandelier Tuff consists of two major volcanic depositions (i.e., the deeper Otowi Member and the uppermost Tshirege Member) and some minor airfall deposits (e.g., the Guaje Pumice Bed and the Cerro Toledo interval). Both major members of the Bandelier Tuff are variably visible across the Pajarito Plateau, with the Tshirege Member forming the most prominent mesas. Both members of the Bandelier Tuff are thickest nearest the Jemez Mountains (their volcanic source) and thin toward their eastern reaches near the Rio Grande.

The basaltic rocks of the Cerros del Rio volcanic field occur in the subsurface below much of the Pajarito Plateau. These lava deposits were erupted from numerous vents both east and west of the Rio Grande. In the vicinity of the Pajarito Plateau, these basalts form a north-south trending highland, now buried by the Bandelier Tuff. Beneath Mesita del Buey, the location of the top of the regional aquifer has been observed in the Cerros del Rio basalt. The general stratigraphy of the Pajarito Plateau can be seen in the photograph in Figure 1.

Mesita del Buey consists of the Tshirege Member of the Bandelier Tuff, which is about 280 ft thick at the location of MDA H. The canyons flanking Mesita del Buey near MDA H also expose the Tshirege Member of the Bandelier Tuff, which is underlain by 100 ft of Otowi Member tuff and 20 ft of Guaje Pumice. Below the Guaje Pumice is 800 ft of Cerros del Rio basalt. The regional aquifer occurs at a depth of about 1000 ft beneath the surface of MDA H in the Cerros del Rio basalt.

Not all the rock units visible in the photograph are visible in outcrop at MDA H, but all are present there. Two rock units beneath MDA H (and visible in Figure 1) are highly fractured. One is the moderately welded tuff unit into which the vertical shafts were bored (i.e., unit 2 of the Tshirege Member of the Bandelier Tuff), and the other is a deep basalt layer underlying the less densely nonwelded tuff beneath the disposal shafts (i.e., units 1 of the Tshirege Member and the Otowi Member).

Certain characteristics of the Otowi and Tshirege Members of the Bandelier Tuff in outcrop can be seen in Figure 2. While both these rock layers are volcanic depositions, they differ in terms of the potential for fractures to provide a groundwater flow path. One difference visible in the outcrop is that parts of the Tshirege Member form steep cliffs, while the Otowi Member forms shallower slopes. This difference in erosion reflects a difference in the degree of welding between the two depositions. Parts of the Tshirege Member are moderately welded, which means they are dense, compacted, and susceptible to fracturing. In contrast, the Otowi Member is generally nonwelded and unfractured.

Generally, the tuff units are more welded toward their western reaches and less welded toward the east. This relationship reflects the relative temperature at which the tuff was deposited: the hottest temperature nearest the source.

In addition to difference in the occurrence of fractures in tuff of various degrees of welding, differences also occur in the characteristics of fractures within units. Numerous field studies indicate substantial variability in the following characteristics of fractures measured within the Tshirege Member of the Bandelier Tuff:

- number and spacing of fractures
- width or aperture of fractures
- coatings or fillings in fractures
- orientation or dip of fractures
- length of fractures
- connectivity between stratigraphic units

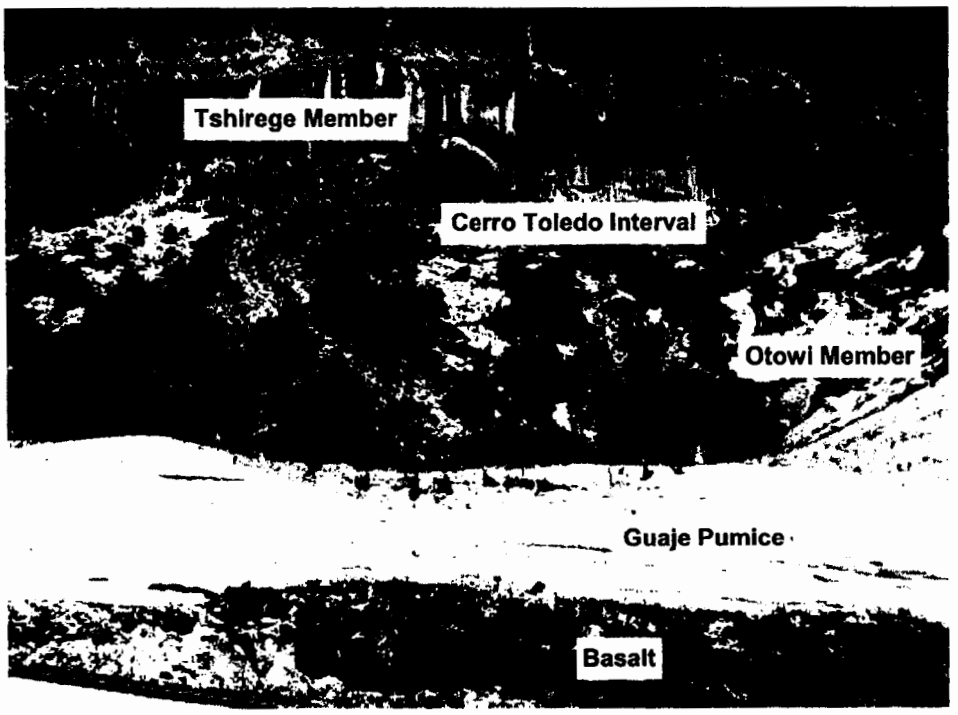

Figure 1. General stratigraphy of the unsaturated zone of the Pajarito Plateau

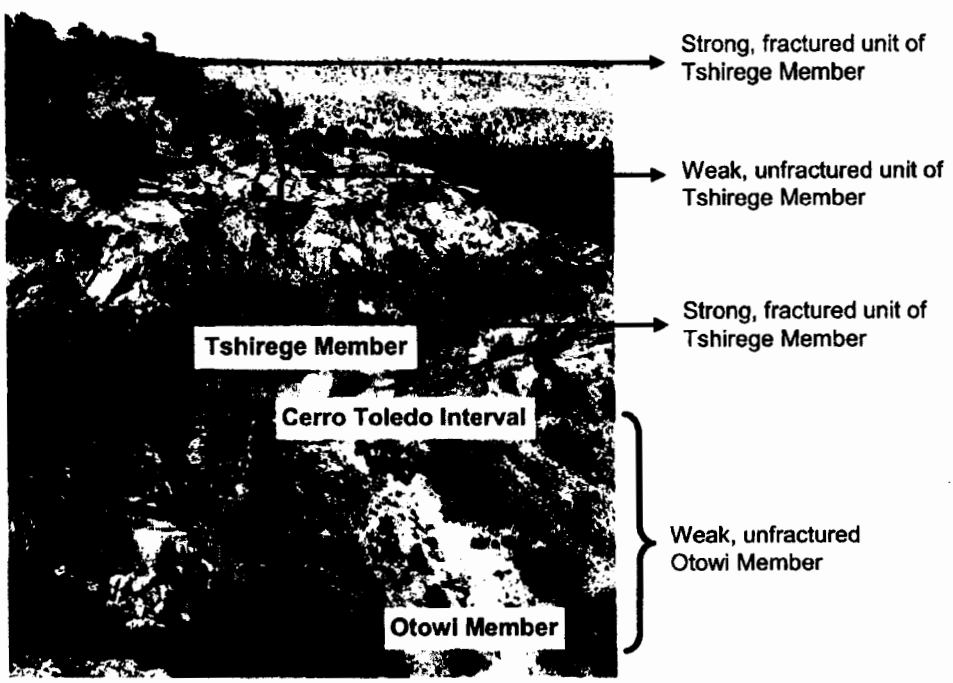

Figure 2. Outcrop of Tshirege tuff, Cerro Toledo sediments, and Otowi tuff

The Laboratory has mapped these characteristics on the walls of excavated pits and trenches at several MDAs, including MDA G and MDA J at TA-54 (Krier et al. 1997, 56834; Rogers 1977, 57818; LANL 2002, 73270). The characteristics of fractures measured in an excavated disposal trench at MDA J, which is adjacent to MDA H on Mesita del Buey, are listed in Table 1. These variable fracture characteristics, along with the porosity and permeability of the fractured rock matrix, influence the flow of groundwater. Fractured rocks with high matrix porosity and permeability, such as the moderately welded members of the Bandelier Tuff, have strong fracture-matrix interaction such that they quickly absorb water into their rock matrices. In lower permeability and porosity rocks, such as the densely welded member of the Bandelier Tuff found on the western margin of the Laboratory, fracture-matrix interaction is weaker and absorption is less rapid. Fracture coatings (or linings) and fracture fillings are generally clay-rich and have low permeability. Coatings and fillings tend to produce opposite effects in terms of fracture flow (Soll and Birdsell 1998, 70011). That is, the presence of coatings can lower fracture-matrix interaction, thus propagating fracture flow. Low permeability clay filling blocks the fracture aperture and impedes fracture flow. The preponderance of clay-filled fractures observed in the Tshirege Member on Mesita del Buey (Table 1) indicates that flow is difficult to sustain in most fractures at the site.

Table 1
Fracture Data from an Excavated Trench at MDA J

Fracture ID	Distance Between Fractures (ft)	True Dip	Aperture (in.)	Filling
1	0	90	0.5	Clay-filled
2	4.25	80	0.5	Clay-filled
3	9.5	90	2	Clay-filled
4	16.42	80	1	Clay-filled
5	9.67	na*	0.2	Clay-filled
6	2.083	70	0.3	Part clay-filled
7	0.83	80	0.2	Clay-filled
8	3.33	42	0.1	Clay-filled
9	1.33	70	0.05	Calcite-lined
10	13.17	58	0.2	Clay-filled, calcite-lined
11	11.42	70	0.1	Clay-filled
12	5	85	0	None
13	4.67	66	0.2	Calcite-filled
14	3	65	0.1	None
15	7.17	80	0.75	Clay-filled
16	2.67	55	0.5	Clay-filled
17	4.17	75	1	Open, calcite-lined
18	5.83	na	0	None
19	10.17	na	0.1	Clay-filled
20	15	90	0.1	Clay-filled
21	3.75	80	0.75	Clay-filled
22	3.67	90	1	Clay-filled
23	2.58	80	0.1	Clay-filled
24	3.5	90	0.5	Clay-filled
25	14.5	88	6	Rubble-filled
26	8	90	0.5	Clay-filled
27	8.33	89	0.3	Clay-filled

Source: LANL 2002, 73270.

*na = Not available.

Table 2 summarizes fracture data measured in several disposal pits at MDA G, which is also on Mesita del Buey but lower in the stratigraphy than MDA H.

Table 2
Fracture Characteristics of Tshirege and Otowi Tuff Units at MDA G

Fracture Characteristic	Tshirege Member, Unit 2	Tshirege Member, Unit 1	Otowi Member
Spacing (m)	1–1.3	Few observed	Few observed
Aperture width (mm)	3	No data	No data
Dip (degrees)	87	No data	No data
Open (%)	~20	No data	No data
Filled (%)	~80	No data	No data
Degree of welding	Moderate	Nonwelded	Nonwelded
Moisture Content	2% by volume	9% by volume	11% by volume
Porosity	46%	48%	44%

Source: Krier at al. 1997, 56834

Data on fractures in deeper rock layers are generally obtained from outcrops, like those shown in Figures 1 and 2. Outcrop observations indicate few fractures in the Otowi Member and rare fractures in the Guaje Pumice bed. Outcrop observations reveal relatively frequent (~0.3 m spacing), open-aperture (~0.5 mm) fractures in the Cerros del Rio basalt (Krier et al. 1997, 56834).

2.2 Hydrology

The movement of liquid water through rock depends primarily upon the physical characteristics of effective porosity and permeability. Effective porosity refers to the amount of interconnected void space (pores) in the rock and represents a flow path for fluids (both vapor and liquid). Permeability is a measure of the ease with which fluids flow through rock; permeability is the opposite of resistance to flow. Rocks with high effective porosity may have high permeability, but high effective porosity is not a requirement for high permeability. For example, rocks with low effective porosity may have very high permeability if open, unfilled fractures are present (e.g., some basalts), and rocks with high effective porosity may have low permeability if the effective pore space is tight or tortuous or if fractures in the rock are clay-filled (e.g., some tuffs).

In addition to physical characteristics of the rock, the movement of water through rock also depends upon the amount of water present, which is referred to as the degree of saturation. In fully saturated rock, all pore space is filled with liquid water. Water moves most quickly through highly permeable, low porosity rock under saturated conditions. The maximum rate of water flow in saturated rock is referred to as the rock's saturated hydraulic conductivity. In high porosity, low permeability rocks with open fractures, liquid water flows readily through fractures when the pore space is saturated with water. Under conditions of partial saturation, liquid water flows preferentially into pore spaces rather than along fractures, unless fractures are continuously clay-lined. However, in this case, water must enter directly into the clay-lined fractures from the surface, since water in the porous matrix will not preferentially flow through the clay lining into a fracture.

As shown in Table 2, the rock types comprising the mesa at MDA H have the following general characteristics relevant to fracture flow (Krier et al. 1997, 56834):

- Unit 2 of the Tshirege Member of the Bandelier Tuff is moderately welded, unsaturated (~2% moisture content by volume) and porous (~46%), and contains frequent (1-m spacing) near-vertical (87°) fractures, most of which (~80%) are clay-filled.
- Unit 1 of the Tshirege Member of the Bandelier Tuff is nonwelded, unsaturated (~9% moisture content by volume) and porous (~48%), and contains few observed fractures.
- The Otowi Member of the Bandelier Tuff is nonwelded, unsaturated (<12% moisture content by volume) and porous (~ 44%), and contains few observed fractures.

Fracture characterization data for deeper rock layers underlying the mesa at MDA H are available only indirectly from observations at other locations across the plateau where these units are visible in outcrops. Outcrops indicate that fracturing is rare in the Guaje Pumice Bed and frequent (0.3 m spacing) in the Cerros del Rio basalts. Pumiceous rock is highly porous and has permeability similar to the nonwelded tuffs. The basaltic rock at the site is heterogeneous in porosity and permeability.

Unsaturated conditions prevail in the Bandelier Tuff deposits at most locations across the Pajarito Plateau. The western reaches of the plateau are the wettest, and recharge of the regional aquifer is generally considered to occur along the eastern flanks of the Sierra de los Valles. Limited, relatively localized saturation exists in alluvium and deeper perched horizons beneath several canyons draining the plateau. Continuous regional saturation occurs in the pre-Bandelier deposits. The Cerros del Rio basalts are variably (un)saturated across the plateau. Beneath MDA H, the upper portion of the Cerros del Rio basalts is unsaturated, and the deeper portion is saturated.

Water has been observed to flow in fractures in densely welded portions of unit 3 and unit 4 of the Tshirege Member of the Bandelier Tuff, which form the mesas at TA-16. In particular, these subunits have localized low porosity (20–40%), low saturated hydraulic conductivity (10^{-9} cm/s) and support large open fractures in the area of TA-16 where fracture transport has been observed (LANL 2003, 77965). In addition, TA-16 is located on the wetter western portion of the Laboratory. Consequently, localized fracture flow is considered to be a significant mode of water flow at that location.

A field experiment was conducted in the 1960s to test the water storage capacity and hydrology of the moderately welded unit 3 caprock at TA-51, which is near TA-54 but slightly higher in the Tshirege Member stratigraphy. This injection well test featured an open borehole in unit 3 of the Tshirege Member into which several thousand gallons of water were pumped over several months. The injection well was surrounded by a circular array of instrumented boreholes within which moisture was monitored throughout the injection period and for several months after injection ceased (Purtymun 1989, 06889). The symmetrical distribution of moisture around the injection well indicated uniform matrix flow in both units 3 and 2, even under conditions of high water content and pressure.

At TA-54, water has been observed in fractures on the exposed walls of disposal pits excavated into moderately welded portions of unit 2 following precipitation events (Rogers 1977, 57818). However, fracture flow was not specifically observed beneath the infiltration pit or in disposal pit walls during a controlled, long-term (230 days) experiment that introduced a large volume (>11,000 gal.) of water into an infiltration pit set back 3 m from the disposal pit (Rogers 1977, 57818).

Fracture transport of an applied bromide tracer has been measured within the Cerros del Rio basalt at the Laboratory. These measurements were taken between 2002 and 2003 at a location near the intersection of State Route 4 and State Route 502 (the "Y"), where the Cerros del Rio basalt was exposed during

excavation and construction of the flood retention structure built by the US Army Corps of Engineers following the Cerro Grande fire (Stone et al. 2004, 87379). At this location, runoff water is ponded by the flood retention structure, creating conditions that initiate fracture flow in the basalt. The boreholes are instrumented with FLUTE membranes, wired pairs, and an INW probe to measure moisture and bromide concentrations.

Field experiments have also been conducted to determine when and if saturated conditions occur episodically under natural conditions at locations that are predominantly unsaturated. Such conditions might initiate localized fracture flow. One such investigation monitored moisture at the soil/tuff interface along a transect on Mesita del Buey at TA-51, less than a mile northwest of MDA H, very near the location of the injection-well test described above (Purtymun 1989, 06889). Moisture data were collected over 15 yr from 11 shallow observation boreholes aligned along a north-south transect across the mesa. In addition to moisture monitoring, water collecting at and flowing along the soil/tuff interface (called the "interflow") was measured for five years.

The interflow trench experiment showed the interface at the bottom of the soil profile and the top of the tuff may become saturated under certain conditions. When saturation occurs, water flows laterally along the soil/tuff interface. Interflow at the soil/tuff interface occurred at a frequency of about one event per year, generally in the spring when snow is melting. Table 3 lists the dates when interflow was measured, along with the volume of the flow. Event durations were one to four days long, and the flow rate for the average event was about 0.66 L per day per meter along the 12-m-long trench. The cumulative amount of interflow along the trench over the entire monitoring period was approximately 32 L and the average volume per flow event was approximately 8 L.

Table 3
Soil/Tuff Interflow Data from TA-51 Trench

Date of Interflow Event	Interflow Volume (L)
11/12/94	1.3
02/13/95	0.9
02/14/95	0.1
02/15/95	10.6
02/16/95	0.2
03/09/97	1.0
03/10/97	7.1
03/11/97	9.3
03/12/97	0.4
01/30/98	0.4
01/31/98	0.3
02/01/98	0.4
02/02/98	0.3
Number of interflow events in 4 yr	4
Average volume per event (L)	8.1
Total interflow volume over 4 yr (L)	32.2

While not observed, it is possible that water intermittently collecting at the soil/tuff interface could flow laterally along the soil/tuff interface and drain into an open fracture, thus initiating transient fracture-flow events even under generally unsaturated conditions. On the occasion when wet fractures in unit 2 were observed in the pit walls at MDA G at TA-54 (see above), water was also observed collecting and flowing along the soil/tuff interface (Rogers 1977, 57818).

3.0 CONCEPTUAL MODEL OF FRACTURE-FACILITATED CONTAMINANT TRANSPORT

Using the current state of knowledge regarding hydrology and geology in fractured rock summarized above, a conceptual model was developed that hypothetically initiates fracture flow at MDA H and maximizes the potential for fractures to transport soluble contaminants from the disposal shafts vertically downward toward the regional aquifer.[1] The assumptions in the model are conservative and overestimate contaminant transport and the potential risk. The conceptual model assumes the following.

- Open, coated, and continuous fractures are present in units 1 and 2 of the Tshirege Member of the Bandelier Tuff, and these fractures conduct water periodically when sufficient water is present at the soil/tuff interface; otherwise, water flows only through the matrix in these layers.
- Open, coated, and continuous fractures are absent in the surface soil, the Otowi Member of the Bandelier Tuff, and the Guaje Pumice Bed, and water continuously flows only through the matrix in these layers.
- Open fractures are present in the basalt beneath the Guaje Pumice Bed, and water always flows preferentially through fractures and not through the matrix in this layer.
- Open, coated, and continuous fractures are ideally oriented to maximally intersect and open into the disposal shafts at MDA H.
- Saturated conditions occur once annually at the soil/tuff interface as a result of interflow.
- When saturated conditions exist at the soil/tuff interface, water flows directly into open, coated, and continuous fractures.
- Water flowing in fractures is conducted directly into the disposal shafts at MDA H.
- Water flowing from fractures into the disposal shafts at MDA H collects at the bottom of the shafts and dissolves contaminants present in the waste.
- Water containing dissolved contaminants in concentrations equal to contaminant-specific solubility limits flows out of the shafts through another ideally oriented, open, coated, and continuous fracture through the Tshirege tuff.
- Water continuously infiltrates surface soil and Tshirege tuff matrix above the disposal shafts and percolates through the disposal shafts, dissolving contaminants throughout the shafts according to their solubility limits and transporting contaminants through the Tshirege tuff beneath the disposal shafts.
- Water and dissolved contaminants are transported into the Otowi Member tuff matrix from fractures and matrix at the base of the Tshirege tuff.
- Dissolved contaminants are transported through the Otowi Member tuff matrix and then through the Guaje Pumice matrix.
- Dissolved contaminants are transported into and through fractures in the basalt from the base of the Guaje Pumice matrix.

[1] While "stair-stepping" fracture flow could also be hypothesized, a vertical path provides the most direct connection between waste and the regional water-supply aquifer.

- Dissolved contaminants flow from fractures in the basalt directly into a hypothetical drinking water supply well.
- A hypothetical member of the public drinks 2 L of contaminated drinking water per day for 70 yr.

Data from the interflow field study (Table 3) were used to formulate a model for periodic annual saturation at the soil/tuff interface that may initiate fracture flow. Using the fracture flow characteristics (Tables 1 and 2), the approach illustrated in Figure 3 was used to scale the interflow flux measured along the 12-m trench to the effective length of fractures available within the MDA H shaft field, which was calculated to be 16 m. Based on this approach, the volume of water available to flow from the saturated soil/tuff interface into a fracture at MDA H is 10.4 L per interflow event. One 24-hr interflow event per year is assumed in the fracture-flow simulations.

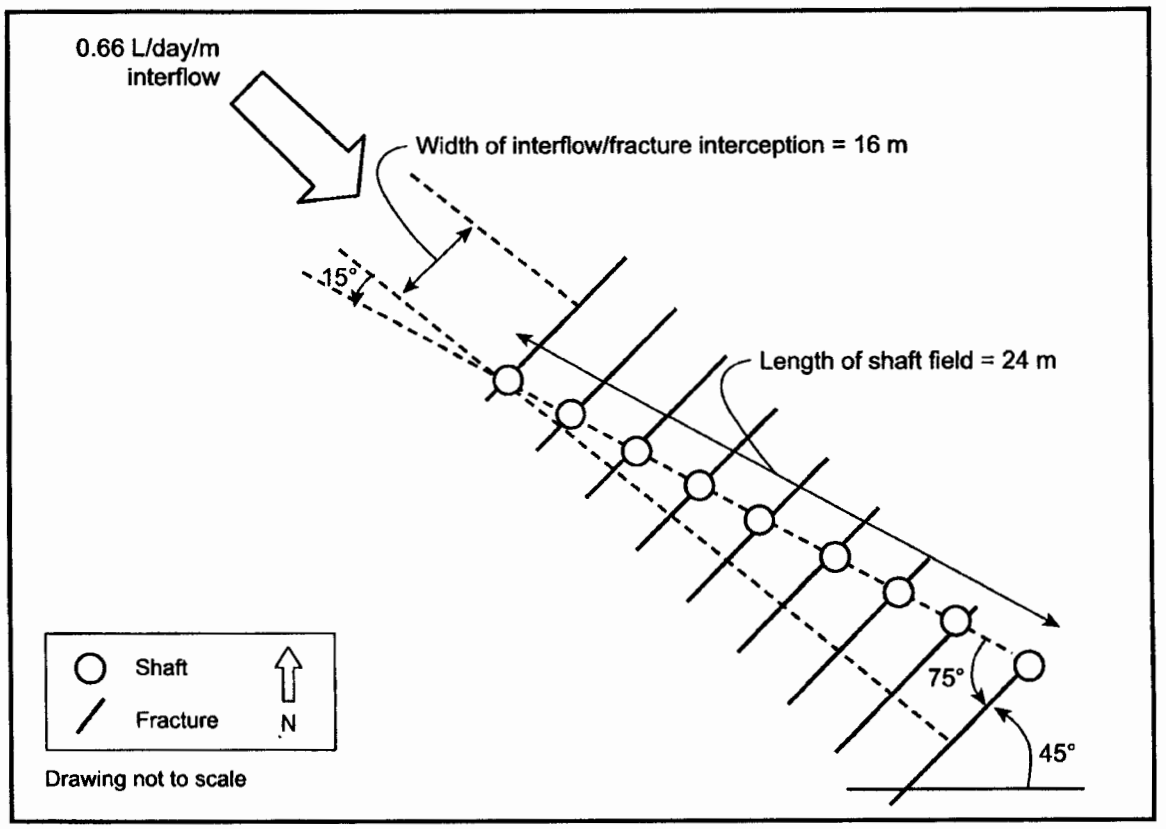

Figure 3. Calculating flux into fractures at MDA H using interflow-trench and fracture-mapping data

MDA H was the Laboratory's primary disposal area for classified solid-form waste. The waste inventory disposed at MDA H was approximately 57% metal, 24% radioactive materials, 9% plastics, 9% graphite, 1%lithium compounds, and <1% high explosives and paper. The maximum dissolution of constituents in water is governed by the compound's solubility limit.

The water from the annual interflow event was assumed to saturate a fraction of the collective inventory of the nine shafts (Table 4). That collective inventory was distributed within a cylindrical volume with a

diameter equal to the composite diameter of the 9 shafts (18 ft). The contaminants in the saturated fraction of the inventory were assumed to dissolve at their solubility limits (Table 5), and then flow out of the disposal shafts vertically downward through an open, coated fracture in the Tshirege tuff.

Table 4
Constituents of the MDA H Inventory

Inventory Constituent	Mass Distribution in Shafts (g)		Inventory Distribution (moles)	
	Lower Part[a]	Total	Lower Part[a]	Total
Silver	1.27E+04	1.77E+04	1.18E+02	1.64E+02
Aluminum	1.91E+07	2.68E+07	7.06E+05	9.92E+05
Barium	1.68E+06	2.40E+06	1.22E+04	1.75E+04
Beryllium	2.09E+06	2.95E+06	2.32E+05	3.27E+05
Cadmium	6.35E+03	8.94E+03	5.65E+01	7.95E+01
Chromium	6.35E+05	8.94E+05	1.22E+04	1.72E+04
Copper	7.71E+05	1.08E+06	1.21E+04	1.70E+04
Cyanuric Acid	1.81E+06	2.40E+06	1.41E+04	1.86E+04
Iron	4.99E+07	7.08E+07	8.93E+05	1.27E+06
Tritium	1.54E-02	1.76E-02	5.14E-03	5.87E-03
Mercury	4.17E+05	5.90E+05	2.08E+03	2.94E+03
Lead	2.49E+07	3.54E+07	1.20E+05	1.71E+05
Plutonium-238	4.99E-06	4.99E-06	2.10E-08	2.10E-08
Plutonium-239	4.54E-02	4.54E-02	1.90E-04	1.90E-04
Plutonium-240	2.95E-03	2.95E-03	1.23E-05	1.23E-05
Plutonium-241	9.98E-05	9.98E-05	4.14E-07	4.14E-07
Plutonium-242	9.98E-06	9.98E-06	4.12E-08	4.12E-08
RDX[b]	5.90E+05	6.53E+05	2.66E+03	2.94E+03
Uranium-234	1.50E+03	2.31E+03	6.40E+00	9.89E+00
Uranium-235	1.50E+05	2.31E+05	6.37E+02	9.84E+02
Uranium-236	5.44E+03	8.30E+03	2.31E+01	3.52E+01
Uranium-238	2.81E+07	4.22E+07	1.18E+05	1.77E+05

[a] The "lower part" distribution refers to the portion of the inventory that is saturated by interflow events.
[b] RDX = Hexayhdro-1,3,5-trinitro-1,3,5-triazine.

Table 5
Solubility Limits and
Median Tuff Distribution Coefficients (Kd) for Constituents in the MDA H Inventory

Constituents	Solubility Limit (mole/L)	Reference for Solubility Data	Tuff Kd (mL/g)	Reference for Kd Value
Actinium	1.2E-9	Krier et al. 1997, 56834, Table 13	130	Krier et al. 1997, 56834, Table 7
Silver	5.6E-10	Krier et al. 1997, 56834, Table 13	90	Krier et al. 1997, 56834, Table 7
Aluminum	1.72E-5	Longmire 1999, 70226	141	Longmire 1999, 70226
Americium	1.2E-9	Krier et al. 1997, 56834, Table 13	141	Longmire 1999, 70226
Barium	4.5E-5	Krier et al. 1997, 56834, Table 13	946	Krier et al. 1997, 56834, Table 7
Beryllium	1E-6	Longmire 1999, 70226	250	Longmire 1999, 70226
Cadmium	5E-8	Krier et al. 1997, 56834, Table 13	80	Krier et al. 1997, 56834, Table 7
Cyanuric acid	3.9E-2	Windholz 1983, 34771	0	Windholz 1983, 34771
Chromium	9.88E-9	Longmire 1999, 70226	70	Longmire 1999, 70226
Copper	2.49E-7	Longmire 2001, 70227	10 to 90	Longmire 2001, 70227
Iron	8.88E-7	Longmire 1999, 70226	220	Longmire 1999, 70226
Tritium	Very large	Krier et al. 1997, 56834, Table 13	0	Birdsell 2001, 70241
Mercury	1.84E-5	Longmire 1999, 70226	80	Longmire 1999, 70226
Neptunium	1.3E-4	Krier et al. 1997, 56834, Table 13	2.25 to 7.5	Longmire 1996, 56030
Protactinium	1.3E-4	Krier et al. 1997, 56834, Table 13	50	Krier et al. 1997, 56834, Table 7
Lead	1.6E-6	Krier et al. 1997, 56834, Table 13	25	Krier et al. 1997, 56834, Table 7
Plutonium	2.3E-7	Krier et al. 1997, 56834, Table 13	4.13 to 711	Longmire 1996, 56030
Radium	9.36E-7	Longmire 1999, 70226	200	Longmire 1999, 70226
RDX (high explosive)	2.34E-4	Birdsell 2001, 70241	0	Birdsell 2001, 70241
Thorium	1.9E-10	Krier et al. 1997, 56834, Table 13	500	Krier et al. 1997, 56834, Table 7
Uranium	1.1E-4	Krier et al. 1997, 56834, Table 13	2.61 to 4.85	Longmire 1996, 56030

Note: The shaded constituents are discussed in Section 4.0 of this report.

4.0 NUMERICAL MODEL OF FRACTURE-FACILITATED CONTAMINANT TRANSPORT

The Laboratory's Finite Element Heat and Mass (FEHM) transport computer code (Zyoloski et al. 1997, 70417) was used for both the baseline (matrix-flow) simulations conducted as part of the MDA H CMS (LANL 2003, 76039) and these alternate simulations. The combined matrix-fracture flow conceptual model as it was implemented in the simulation model is shown in Figure 4. The top of the figure shows two columns connected to a single third column on the bottom. The column on the top left of the figure represents matrix flow and contaminant transport through the Tshirege tuff (units 2 and 1), similar to the model used for the baseline risk assessment of MDA H and reported in Appendix J of the MDA H CMS report, although that assessment was done in three dimensions (LANL 2003, 76039). The column on the top right of the figure represents fracture flow through the Tshirege tuff (units 2 and 1). The single column on the bottom of the figure represents matrix flow and contaminant transport through the Otowi Member tuff and the Guaje Pumice Bed, and fracture-dominated flow through the Cerros del Rio basalt, again as

modeled in the baseline risk assessment of MDA H. These columns were numerically modeled as one-dimensional columns.

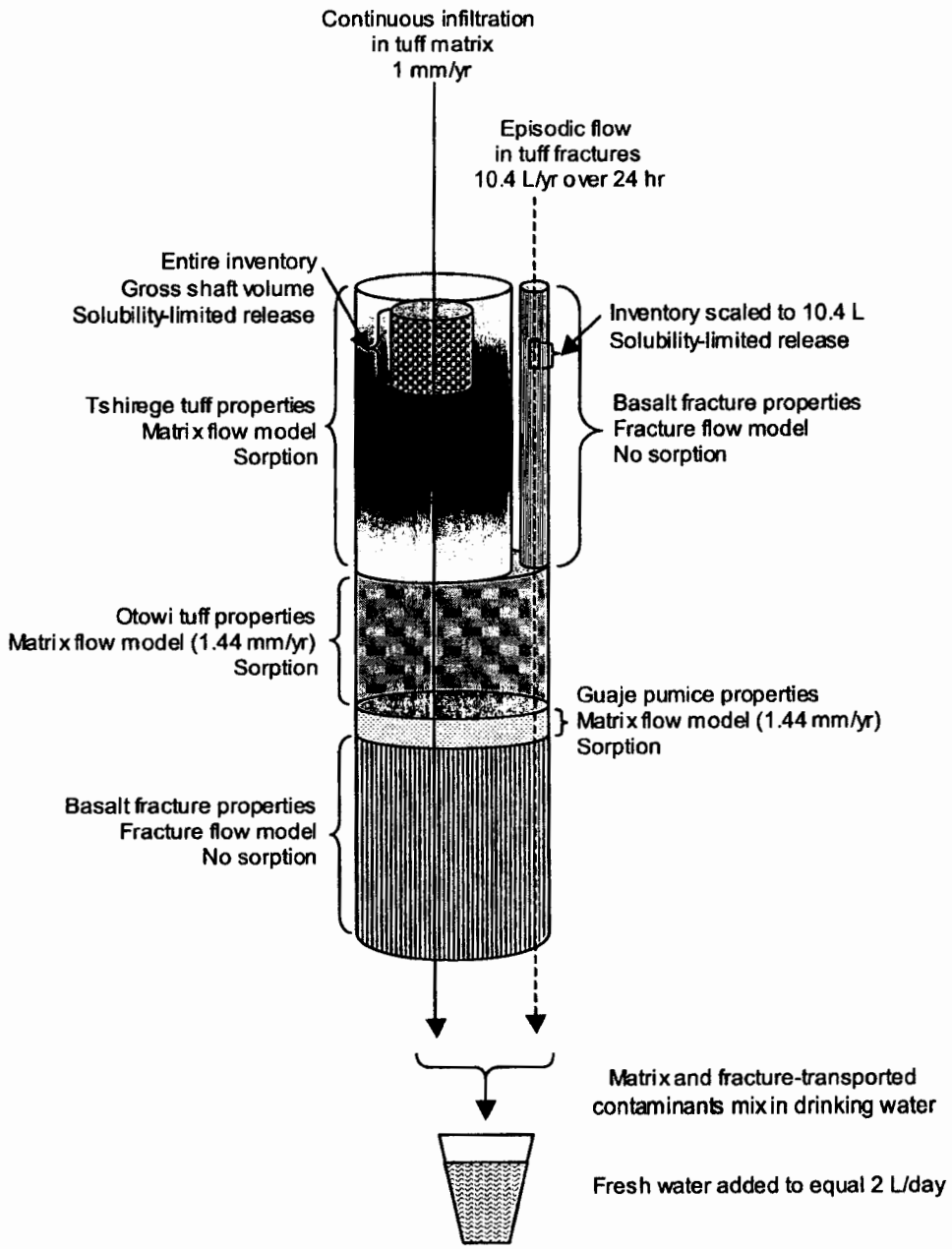

Figure 4. Graphical representation of the computational model

To summarize the numerical model illustrated in Figure 4, groundwater flow and contaminant transport through the two top one-dimensional columns were calculated simultaneously for a period of 1000 yr. The two top Tshirege tuff columns differ in the following respects.

1. Matrix column
   a. Liquid water flows continuously through the Tshirege tuff matrix at a rate of 1 mm/yr.
   b. Contaminants in the MDA H inventory are assumed to be distributed uniformly throughout a cylinder of unit 2 tuff with a volume equal to the combined volume of the MDA H shafts.
   c. Contaminants in the MDA H inventory dissolve into the liquid water moving through the column at a concentration limited only by the contaminants' solubility limits (maximum concentrations).
   d. Contaminants are transported through the Tshirege tuff matrix according to their sorption characteristics.
2. Fracture column
   a. Liquid water is applied to the fractured Tshirege tuff column periodically, initiated when rainwater and/or melting snow create sufficient saturation at the soil/tuff interface. Water is added to the fracture once per year for a 24-hr duration. A total volume of 10.4 L is applied to the fracture column during the one-day event. The volume and frequency are derived from the interflow trench observations discussed previously.
   b. Water in the Tshirege fracture column flows directly through a cylindrical volume representing the bottom of the disposal shafts. The cylindrical volume contains that fraction of MDA H inventory available to the 10.4 L of water introduced by an annual 24-hr fracture flow event.
   c. Contaminants in the fraction of waste in the bottom of the saturated shafts are dissolved into the water in concentrations controlled by the contaminants' solubility limits.
   d. Dissolved contaminants flow directly from the volume of available inventory into an open, coated fracture that continues through the Tshirege tuff. Dissolved contaminants do not sorb to the fracture coating, nor is groundwater containing dissolved contaminants absorbed into the tuff matrix.

The rationale for the matrix flow and transport through the variably fractured Tshirege tuff units is taken from a modeling study conducted to reproduce the results of the injection-well test discussed previously (Purtymun et al. 1989, 06889; Robinson et al. 2004, 87378).[2] Similarly, a modeling study of Los Alamos Canyon shows that a matrix model for the Otowi Member of the Bandelier Tuff matches field moisture contents. For Los Alamos Canyon, the matrix model is adequate despite the presence of a perched alluvial aquifer atop the Otowi Member and estimated percolation rates ranging from 200 to over 1000 mm/yr from the perched system directly into the Otowi Member. If the matrix model adequately captures field behavior under these saturated, high-infiltration conditions, it is even more likely to apply for the very dry, slow infiltration rates estimated for MDA H. The matrix transport simulations incorporated the vanGenuchten model (vanGenuchten 1980, 49927) to represent the moisture retention characteristic

[2] Recent analyses performed since the release of the MDA H CMS (Robinson et al. 2004, 87378) evaluated several alternative conceptual and numerical approaches to groundwater flow to determine which most accurately reflected the injection-well test data. The results of this study indicate that unsaturated flow and transport through fractured moderately welded Bandelier Tuff is best represented as matrix-dominated flow, rather than fracture-controlled flow. If fractures are included in the model, field behavior is only represented when fracture-matrix interaction is strong enough to absorb water quickly into the matrix. This behavior is in part a result of the high matrix permeability of the moderately welded Bandelier Tuff.

curves for flow in all the stratigraphic units. The hydrologic parameters listed in Table 6 (saturated hydraulic conductivity, porosity, etc.) are fairly well characterized for the Bandelier Tuff units but not for the deeper units. The properties for the tuff units (Krier et al. 1997, 56834) and the Guaje Pumice were measured on core samples of matrix material.

Table 6
Hydrologic Parameters Used in the Fracture-Facilitated Transport Model

Unit	Ksat[a] (cm/s)	Porosity	vanGenuchten θ_r, α (cm^{-1}), n[b]
Tshirege Member, unit 2[c] matrix column	4.27×10^{-4}	0.481	0.013, 0.0060, 1.890
Tshirege Member, unit 1[c] matrix column	1.48×10^{-4}	0.517	0.002, 0.0030, 1.932
Tshirege Member, unit 2[d] fracture column	8.8×10^{-4}	0.001	0.0, 0.0384, 1.474
Tshirege Member, unit 1[d] fracture column	8.8×10^{-4}	0.001	0.0, 0.0384, 1.474
Otowi Member[c]	2.49×10^{-4}	0.435	0.0188, 0.0059, 1.713
Guaje Pumice[e]	1.5×10^{-4}	0.667	0.0, 0.00081, 4.0264
Cerros del Rio basalt[f]	8.8×10^{-4}	0.001	0.0, 0.0384, 1.474

[a] Ksat = Saturated hydraulic conductivity.

[b] θ_r = Residual moisture content (volume percent). α, n = vanGenuchten fitting parameters (vanGenuchten 1980, 49927).

[c] Mean values from Krier et al. (1997, 56834).

[d] Basalt fracture properties from Stone et al. 2004, 87379.

[e] Springer et al. 2000, 71097.

[f] Stone et al. 2004, 87379.

The basalt was modeled as a fractured, single-porosity medium with the properties based on calibration of the model to field measurements of fracture transport from the low-head weir site mentioned previously (Stone et al. 2004, 87379). The properties do not allow for any fracture-matrix interaction; as a result, any water entering the basalt flows through a medium of very low porosity. Therefore, transport occurs quickly through the medium. The fractured basalt properties are used as well for units 1 and 2 of the Tshirege Member fracture column to prevent liquid in fractures from being absorbed into the matrix, despite the fact that a strong fracture-matrix interaction is expected in these two units. This representation maximizes water flow through the upper fracture column and minimizes transport time.

The upper boundary condition for the matrix column was a continuous (or steady-state) water flux of 1 mm/yr, representing surface water infiltrating into and through the subsurface rock. Based on several corroborating data sets, the assumption of continuous water flux (however small) is the base case estimate of the actual amount and rate of water moving downward through the mesa (Krier et al. 1997, 56834; Bergfeld and Newman 2001, 71246; Rogers et al. 1997, 63131). Measurements of porewater chloride concentrations are often used to estimate flux. For example, high porewater chloride concentrations observed across Mesita del Buey lead to flux estimates ranging from 0.03 to 1.5 mm/yr (Newman 1996, 59372). More recent chloride data from borehole 54-01023 at MDA H yield a water flux of 0.2 mm/yr to a depth of 140 ft (Bergfeld and Newman 2001, 71246). The chloride analysis indicates a chloride accumulation time in excess of 1000 yr. This 1000-yr evaluation period is the same as that considered in the baseline risk assessment performed for the CMS. Previous numerical simulations indicate that evaporative effects can reasonably account for the low moisture contents observed in undisturbed regions of the mesa at the site and a low net percolation rate (Birdsell et al. 1999, 69792).

The entire inventory of the nine MDA H disposal shafts, listed in Table 4, was considered in the fracture-flow transport model. In the matrix column of the computation, water continuously flowing at a rate of 1 mm/yr encountered the total mass of each contaminant, distributed over a volume equal to the composite volume of the nine shafts. In the fracture column, 10.4 L of water encountered a fraction of the total mass, namely, the mass within a 10.4 L volume in the lower portion of a composite shaft.

In both the matrix and fracture columns, contaminants were allowed to dissolve at their maximum solubility limits, which are listed in Table 5. Sorption of contaminants in the tuff matrix columns was calculated according to distribution (or sorption) coefficients (Kd values) based on site-specific experiments where available and otherwise were taken from the Yucca Mountain literature (Longmire et al. 1996, 56030; Krier et al. 1997, 56834). Data in Table 5 are taken from Appendix J of the MDA H CMS report (LANL 2003, 76039).

Highly soluble and nonsorbing constituents in the MDA H inventory are expected to be transported most readily. The shaded rows in Table 5 indicate the most soluble elements in the inventory, cyanuric acid and tritium, and the three nonsorbing contaminants, cyanuric acid, tritium, and RDX. Transport of cyanuric acid, tritium, and RDX were modeled using FEHM.

Figure 5 shows the time-dependent arrival of cyanuric acid and RDX at the bottom of both the tuff-matrix and the fractured-tuff column at the Tshirege/Otowi interface (shown in Figure 4). The early transient arrival is from the fracture column, while the later arrival is from the matrix column. The molar flux from the fracture column decreases as the available contaminant mass is dissolved and the source is depleted. In the case of tritium (not shown), radioactive decay depletes the source by 26 orders of magnitude over the 1000-yr simulation period, with a maximum concentration of 1E-20 pCi/L after 625 years at the Tshirege/Otowi interface.

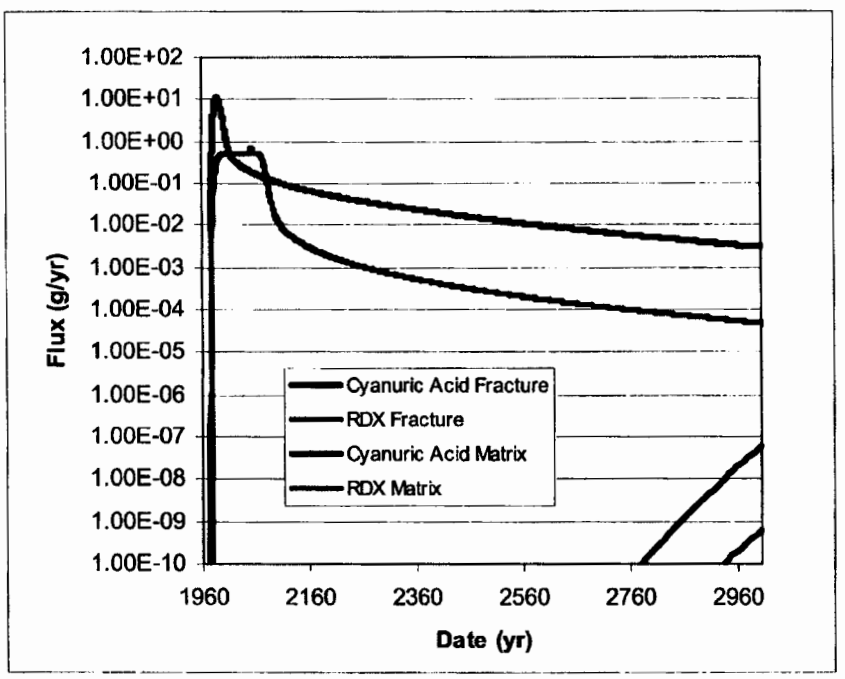

Figure 5. Flux of cyanuric acid and RDX as input into the Otowi Member tuff matrix column from the Tshirege tuff matrix and fracture columns

Water and contaminant fluxes from both the fractured and matrix Tshirege tuff columns feed into a single column within a layer that represents the Otowi Member tuff. According to the matrix model, contaminated water is transported through the Otowi Member tuff and Guaje Pumice into the bottom layer of the bottom column, which represents the Cerros del Rio basalt. Contaminated water flows through the fractures in the basalt (without sorption) directly into a drinking water supply. Contaminants are transported through the Otowi Member and the Guaje Pumice according to their sorption characteristics and a continuous infiltration rate of 1.44 mm/yr, which is the time-averaged combined rate of water flow from the two upper columns.

The simulated travel time for water (and nonsorbing contaminants) from the base of the fracture Tshirege Member to the regional aquifer is 8000 yr under the specified flux. No contaminants enter the regional aquifer over 1000 yr, even when accounting for rapid transport of a fraction of the inventory through fractures. This result applies for any sorbing species as well. Figure 6 shows the concentration of cyanuric acid and RDX at 1000 yr, as a function of depth within the bottom combined column shown in Figure 4. Both the cyanuric acid and RDX are confined within the Otowi Member and do not penetrate below the Otowi Member.

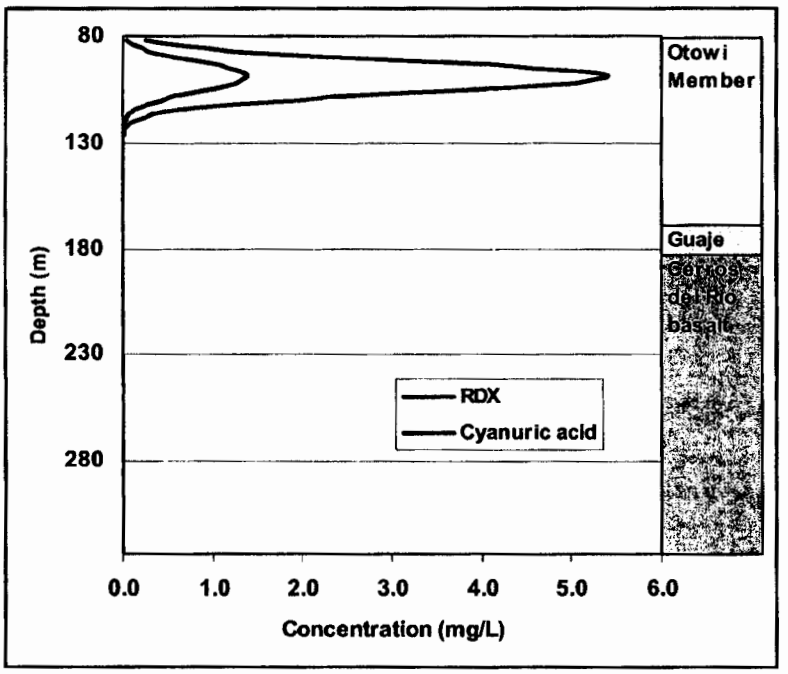

Figure 6. Concentration of cyanuric acid and RDX in the Otowi Member, Guaje Pumice, and Cerros del Rio basalt column at 1000 yr

5.0 RISK ASSESSMENT RESULTS OF FRACTURE–FACILITATED CONTAMINANT TRANSPORT

The risk assessment assumes the EPA default drinking-water ingestion rate of 2 L per day over a 70-yr period. The calculations are conducted over a period of 1000 yr, and the maximum concentrations over any continuous 70-yr interval were used in the risk assessment. The Department of Energy and NMED metrics for human health impacts from contaminated drinking water were used to decide whether or not

"harmful exposures" may occur based on calculated groundwater concentrations. As applied to the MDA H, these decision thresholds are

- calculated concentrations of cancer-causing chemicals in groundwater that result in a calculated incremental cancer risk (ICR) greater than or equal to 1-in-100,000 (i.e., 10^{-5} or 1E-05);
- calculated concentrations of noncancer causing chemicals in groundwater that result in a calculated hazard index (HI)[3] greater than or equal to 1; and
- calculated concentrations of radionuclides in groundwater that result in a calculated total effective dose equivalent (TEDE) greater than or equal to 4 mrem/yr.

Since no contaminants were transported to the regional aquifer over the 1000-yr simulation, there were no health effects, even when rapid transport of a portion of the MDA H inventory was assumed to occur because of fractures in the Tshirege Member of the Bandelier Tuff (and the Cerros del Rio basalt).

6.0 INTERPRETATION OF THE ALTERNATE GROUNDWATER-PATHWAY RISK ASSESSMENT FOR MDA H

The purpose of this assessment is to determine whether an alternate conceptual model of fracture-facilitated transport results in different risks than those calculated using the original matrix-dominated conceptual model. The results shown in Figure 5 indicate that the addition of fracture flow to the matrix flow evaluation decreases the time required for contaminants to be transported through the upper, fractured tuff units. Even with the addition of fracture flow, however, contaminants do not reach the regional aquifer by the end of the 1000-yr evaluation period. Therefore, the alternate conceptual model does not result in risks different from those calculated for the CMS using the original conceptual model. The results of the fracture-flow risk assessment corroborate the recommendations in the MDA H CMS report for stabilization and long-term monitoring and maintenance.

The calculations in the numerical model represent hypothesized assumptions designed to conduct water and solutes through fractures at rates greater than those indicated by field measurements and observations. The calculations represent MDA H in its current configuration, prior to implementation of a corrective measure. The corrective measure recommended in the CMS would include engineered barriers to prevent inflow of water into the shafts and long-term monitoring and maintenance. Thus, the rate of contaminant migration following implementation of the corrective measure would be expected to be less than calculated in this analysis.

Table 7 summarizes the model assumptions in this assessment, the effect of these assumptions on the simulated results, and the field measurements and observations supporting the conservative nature of these assumptions.

[3] An HI is used to characterize potential noncancer health impacts for exposures to more than one hazardous chemical. A hazard quotient (HQ) is used to characterize potential noncancer health impacts for exposures to a single hazardous chemical.

Table 7
Comparison Between the Assumptions of the Conceptual and Numerical Models and MDA H Site Conditions

Model Assumption	Effect of Assumption on Simulated Results	Field Conditions
Open, coated, continuous fractures in Tshirege units 1 and 2; basalt fracture properties; no fracture-matrix interaction.	Water and contaminants are transported quickly through the fracture column; thus, no transfer into the matrix by capillary suction or diffusion can occur.	Most fractures are clay-filled (Table 1) and do not cross units; TA-50 injection experiment indicates strong fracture-matrix interaction and does not indicate fracture flow.
Open fractures maximally intersect shafts.	The maximum likelihood is that a fracture intersects the shafts and thus induces fracture flow.	Fractures are near vertical and few would intersect the shafts.
Saturated conditions at soil/tuff interface occur once annually; lateral flow is diverted down fractures and into shaft.	The volume of interflow water available for fracture flow into shafts is maximized.	Interflow at the soil/tuff interface indicates that lateral transport along the interface is preferred over other directions. The presence of interflow at the trench face indicates water is not being lost to fractures upslope of the trench.
Wastes dissolve at their solubility limits under unsaturated conditions. For the fracture column, this happens over a short time when the bottom of the shaft is assumed to be wet from the fracture flow event.	The maximum possible concentration of a given constituent is used in the source region for both the matrix and the fracture columns.	Dissolution is a kinetic process that is often slow for metals. Waste needs to be very wet for extended periods to dissolve at their solubility limits.
Constituents leaving the unsaturated basalts enter directly into a water supply well with only enough dilution to supply 2 L/day.	This process minimizes dilution.	No water supply well is located beneath MDA H. Travel to a water supply well would further increase travel times and dilute concentrations.

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