

# Preliminary Bounds on the Expected Postclosure Performance of the Yucca Mountain Repository Site, Southern Nevada

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PRELIMINARY BOUNDS ON THE EXPECTED POSTCLOSURE  
PERFORMANCE OF THE YUCCA MOUNTAIN REPOSITORY SITE,  
SOUTHERN NEVADA

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ABSTRACT

Current data and understanding about the site conditions at Yucca Mountain provide a basis for calculating the likely range of performance of a mined repository for spent nuclear fuel. Low flux through the unsaturated zone results in groundwater travel times to the water table that probably exceed 10,000 years and may exceed 100,000 years, far longer than required by the NRC. The low flux will also limit releases of waste from the waste packages, probably to annual amounts less than one millionth of the mass of the waste inventory remaining 1000 years after repository closure; the corresponding releases of curies would be well within the allowable releases set by the NRC. Geochemical retardation by sorption and diffusion will slow radionuclide movement relative to groundwater flow by factors of hundreds to thousands for many waste species. In combination, these site conditions provide a high degree of confidence that no releases to the accessible environment will occur during the first 10,000 years after repository closure, the time period for which the EPA has set release limits. Carbon-14, technetium-99, iodine-129, and various nuclides of uranium sorb poorly on the tuffs along the flow paths and, together with uranium daughter products, will be the first radionuclides to arrive at the water table. The total radioactivity produced by these and later arriving contaminants will remain far below the allowable releases, even for periods of millions of years, if expected flux conditions prevail. If the flux is currently greater than the values inferred from the measured in situ moisture contents of the volcanic rocks or if it were to increase in the future, fracture flow and attendant short flow times to the water table could occur. Even if rapid fracture flow were to occur, release of wastes to the accessible environment would probably remain low with respect to the EPA's limits, because diffusion of radionuclides from the fractures into the rock matrix would ensure slow migration of most of the wastes through the sorbing matrix.

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## CHAPTER 1. INTRODUCTION

### 1.1 Purpose

This report summarizes some current conclusions about the expected performance of a potential repository site at Yucca Mountain in southern Nevada (Figure 1). In particular, the capabilities of the current geologic and hydrologic environments to isolate radioactive wastes placed in a repository located in the unsaturated, densely welded tuffs of the Topopah Spring Member of the Paintbrush Tuff (Figure 2) are addressed in terms of certain regulatory requirements. These requirements are set forth by (1) the Department of Energy (DOE) as "General Guidelines for Recommendation of Sites for Nuclear Waste Repositories" in a November 13, 1983, draft of 10 CFR Part 960 (DOE, 1983); (2) the Nuclear Regulatory Commission (NRC) as "Technical Criteria for Disposal of High-Level Radioactive Wastes in Geologic Repositories" published as a final rule in 10 CFR Part 60 (NRC, 1983); and (3) by the Environmental Protection Agency (EPA) in "Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Wastes," a proposed rule in 40 CFR Part 191 (EPA, 1982; 1984).

The report was prepared for the Nevada Nuclear Waste Storage Investigations (NNWSI) Project, which is administered from the DOE's field office in Las Vegas, Nevada. Data to support our conclusions are abstracted from a number of formal and informal reports generated by technical participants in the NNWSI Project, as well as from a few simple calculations that appear in the following sections. The technical participants who supplied data for this report are primarily from the U.S. Geological Survey, Sandia National Laboratories, Lawrence Livermore National Laboratory, and Los Alamos National Laboratory. However, the interpretations or uses and data that appear in this report are those of the authors.

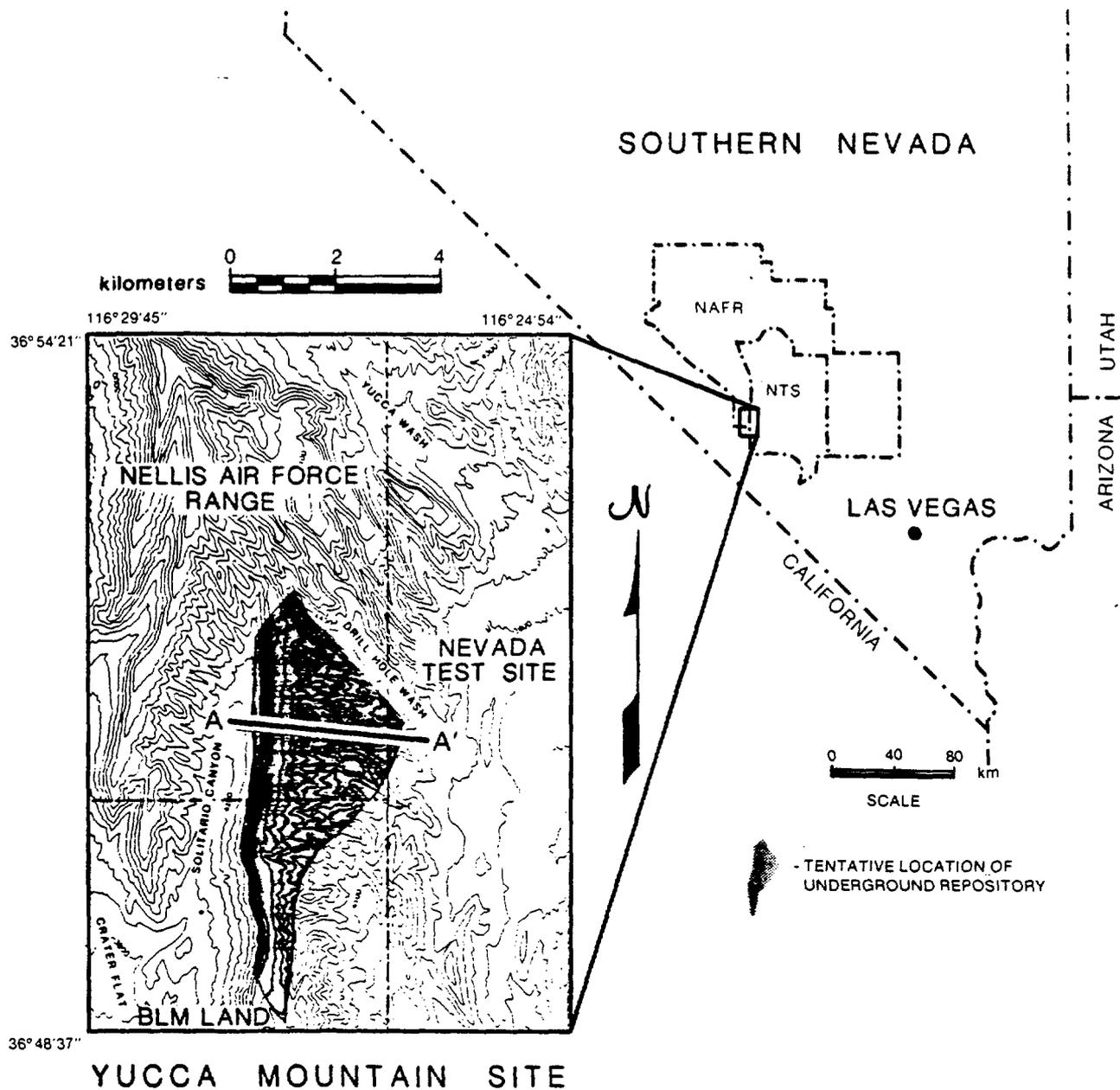


Figure 1. Location of the site for a possible radioactive-waste repository at Yucca Mountain in southern Nevada; A-A' shows the location of the geologic cross section in Figure 2.

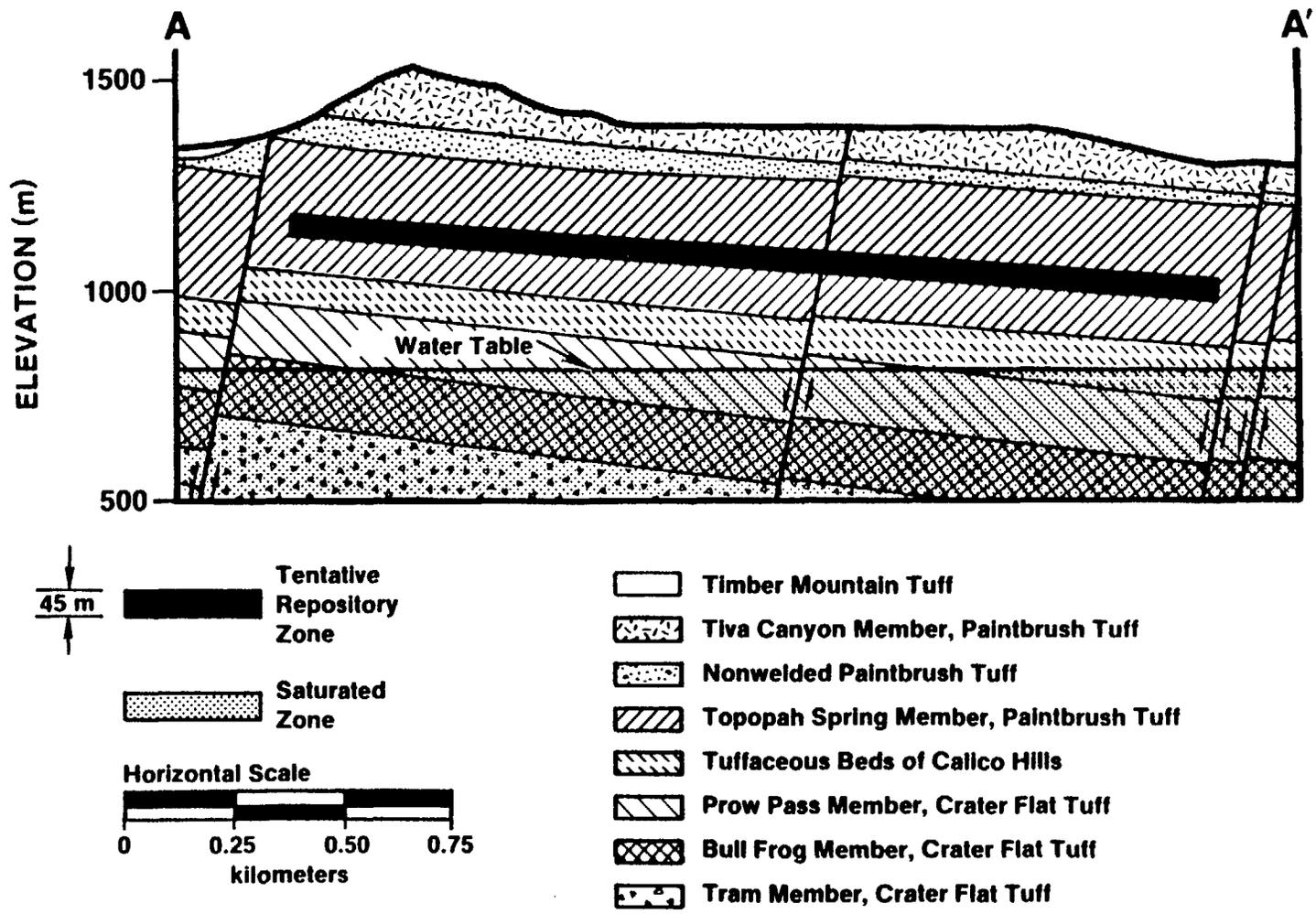


Figure 2. Geologic cross section of Yucca Mountain showing the tentative depth of a possible repository in the Topopah Spring Member of the Paintbrush Tuff.

This report is intended, in part, to provide some of the information required to support an environmental assessment document. If Yucca Mountain is selected by the DOE as one of at least five sites to be nominated as suitable for site characterization, the environmental assessment will be prepared to support that nomination in accordance with the DOE siting guidelines (DOE, 1983) and the Nuclear Waste Policy Act of 1982 (U.S. Congress, 1983). The analyses in this report rely on assumptions about the engineered and site features of a repository that may differ from those eventually used in the environmental assessment. Nonetheless, our conclusions are offered for use by the DOE in its efforts to prepare the environmental assessment, should Yucca Mountain be nominated, or for use in its decision not to nominate Yucca Mountain, should that be the chosen course. However, our broader objective is to organize the current understanding of the natural features of Yucca Mountain in such a way that the reader can begin to form opinions about the suitability of a site at Yucca Mountain for isolating nuclear wastes in an underground repository.

## 1.2 Applicable Regulatory Requirements

Only two regulatory requirements are directly amenable to evaluation in the sole context of natural conditions at Yucca Mountain, and both requirements address the same condition. They are

1. A 1,000-yr pre-waste-emplacment groundwater flow time from the disturbed zone to the accessible environment, an NRC performance objective for the geologic setting of nuclear waste repositories, 10 CFR 60.113(2) (NRC, 1983).

2. A similar requirement for a 1,000-yr flow time from the disturbed zone to the accessible environment, a proposed disqualifying condition of the DOE listed in its technical guideline for geohydrology, 10 CFR 960.4.2.1(d) (DOE, 1983).

The 1000-yr flow-time requirement of the NRC is not rigid, in the sense that mitigating circumstances that would permit compliance with radiological standards may be sufficient to allow the agency to waive the flow-time prescription.

Other regulatory requirements must be evaluated in the context of both natural conditions at a site and engineered components of a repository constructed at that site. The contribution of natural conditions to satisfying these requirements can be assessed only under certain assumptions about the engineered system. In this spirit, we will make the necessary assumptions explicit in order to evaluate the expected performance of the Yucca Mountain site with respect to the following regulations:

1. The annual release rate of any radionuclide from the engineered barrier system after closure of the repository shall not exceed 1 part in 100,000 of the total amount of that radionuclide calculated to be present 1,000 yr after permanent closure. This is an NRC performance objective for the engineered system. These release limits are shown in Table 1. Any radionuclide constituting less than 0.1% of the total release limit is exempt from this requirement, 10 CFR 60.113(a,1,ii,B) (NRC, 1983).

TABLE 1. Radionuclide inventory of spent fuel and allowable release of the NRC and EPA

Isotope	Half Life (yr)	Specific Activity (Ci/g)	Inventory (Ci/1000 MTHM)			Annual NRC Release Limits From Repository (Ci/1000 MTHM),(c)	EPA Cumulative Release Limits at Accessible Environment (Ci/1000 MTHM) <sup>e</sup>
			t = 10 yr <sup>(a)</sup>	t = 360 yr <sup>(b)</sup>	t = 1060 yr <sup>(b)</sup>		
246Cm	5.5 x 10 <sup>3</sup>	2.64 x 10 <sup>-1</sup>	3.5 x 10 <sup>1</sup>	3.4 x 10 <sup>1</sup>	3.1 x 10 <sup>1</sup>	3.1 x 10 <sup>-4</sup> (NA) <sup>(d)</sup>	100
245Cm	9.3 x 10 <sup>3</sup>	1.57 x 10 <sup>-1</sup>	1.8 x 10 <sup>2</sup>	1.8 x 10 <sup>2</sup>	1.7 x 10 <sup>2</sup>	1.7 x 10 <sup>-3</sup> (NA)	100
244Cm	1.76 x 10 <sup>1</sup>	8.32 x 10 <sup>1</sup>	9.0 x 10 <sup>5</sup>	9.3 x 10 <sup>-1</sup>	0	0 (NA)	100
242Cm	4.5 x 10 <sup>-1</sup>	3.32 x 10 <sup>3</sup>	8.5 x 10 <sup>3</sup>	3.5 x 10 <sup>1</sup>	3.2 x 10 <sup>1</sup>	3.2 x 10 <sup>-4</sup> (NA)	100
243Am	7.95 x 10 <sup>3</sup>	1.85 x 10 <sup>-1</sup>	1.4 x 10 <sup>4</sup>	1.4 x 10 <sup>4</sup>	1.3 x 10 <sup>4</sup>	1.3 x 10 <sup>-1</sup>	100
242Am	1.52 x 10 <sup>2</sup>	9.72	1.0 x 10 <sup>4</sup>	3.4 x 10 <sup>3</sup>	3.1 x 10 <sup>1</sup>	3.1 x 10 <sup>-4</sup> (NA)	1000
241Am	4.58 x 10 <sup>2</sup>	3.24	1.6 x 10 <sup>6</sup>	1.8 x 10 <sup>3</sup>	1.7 x 10 <sup>2</sup>	1.7 x 10 <sup>-3</sup> (NA)	100
242Pu	3.79 x 10 <sup>5</sup>	3.90 x 10 <sup>-3</sup>	1.6 x 10 <sup>3</sup>	1.6 x 10 <sup>3</sup>	1.6 x 10 <sup>3</sup>	1.6 x 10 <sup>-2</sup>	100
241Pu	1.32 x 10 <sup>1</sup>	1.12 x 10 <sup>2</sup>	6.9 x 10 <sup>7</sup>	1.8 x 10 <sup>2</sup>	1.7 x 10 <sup>2</sup>	1.7 x 10 <sup>-3</sup> (NA)	100
240Pu	6.58 x 10 <sup>3</sup>	2.26 x 10 <sup>-1</sup>	4.5 x 10 <sup>5</sup>	4.4 x 10 <sup>5</sup>	4.1 x 10 <sup>5</sup>	4.1	100
239Pu	2.44 x 10 <sup>4</sup>	6.13 x 10 <sup>-2</sup>	2.9 x 10 <sup>5</sup>	2.9 x 10 <sup>5</sup>	2.8 x 10 <sup>5</sup>	2.8	100
238Pu	8.6 x 10 <sup>1</sup>	1.75 x 10 <sup>1</sup>	2.0 x 10 <sup>6</sup>	1.6 x 10 <sup>5</sup>	3.2 x 10 <sup>1</sup>	3.2 x 10 <sup>-4</sup> (NA)	100
239Np	6.4 x 10 <sup>-3</sup>	2.33 x 10 <sup>5</sup>	1.4 x 10 <sup>4</sup>	1.4 x 10 <sup>4</sup>	1.3 x 10 <sup>4</sup>	1.3 x 10 <sup>-1</sup>	1000
237Np	2.14 x 10 <sup>6</sup>	7.05 x 10 <sup>-4</sup>	3.1 x 10 <sup>2</sup>	2.7 x 10 <sup>2</sup>	2.7 x 10 <sup>2</sup>	2.7 x 10 <sup>-3</sup> (NA)	100
238U	4.51 x 10 <sup>9</sup>	3.33 x 10 <sup>-7</sup>	3.2 x 10 <sup>2</sup>	3.2 x 10 <sup>2</sup>	3.2 x 10 <sup>2</sup>	3.2 x 10 <sup>-3</sup> (NA)	100
236U	2.39 x 10 <sup>7</sup>	6.34 x 10 <sup>-5</sup>	2.2 x 10 <sup>2</sup>	2.2 x 10 <sup>2</sup>	2.3 x 10 <sup>2</sup>	2.3 x 10 <sup>-3</sup> (NA)	100
235U	7.1 x 10 <sup>8</sup>	2.14 x 10 <sup>-6</sup>	1.6 x 10 <sup>1</sup>	1.6 x 10 <sup>1</sup>	1.6 x 10 <sup>1</sup>	1.6 x 10 <sup>-4</sup> (NA)	100
234U	2.47 x 10 <sup>5</sup>	6.18 x 10 <sup>-3</sup>	7.4 x 10 <sup>1</sup>	7.4 x 10 <sup>1</sup>	7.5 x 10 <sup>1</sup>	7.5 x 10 <sup>-4</sup> (NA)	100
233U	1.62 x 10 <sup>5</sup>	9.47 x 10 <sup>-3</sup>	3.8 x 10 <sup>-2</sup>	4.5 x 10 <sup>-1</sup>	1.3	1.3 x 10 <sup>-5</sup> (NA)	100
231Pa	3.25 x 10 <sup>4</sup>	4.51 x 10 <sup>-2</sup>	5.3 x 10 <sup>-3</sup>	1.3 x 10 <sup>-1</sup>	3.7 x 10 <sup>-1</sup>	3.7 x 10 <sup>-6</sup> (NA)	100
232Th	1.4 x 10 <sup>10</sup>	1.10 x 10 <sup>-7</sup>	1.1 x 10 <sup>-7</sup>	4.1 x 10 <sup>-6</sup>	1.2 x 10 <sup>-5</sup>	1.2 x 10 <sup>-10</sup> (NA)	100
230Th	8.0 x 10 <sup>4</sup>	1.94 x 10 <sup>-2</sup>	4.1 x 10 <sup>-3</sup>	2.2 x 10 <sup>-1</sup>	6.6 x 10 <sup>-1</sup>	6.6 x 10 <sup>-6</sup> (NA)	100
229Th	7.34 x 10 <sup>3</sup>	2.13 x 10 <sup>-1</sup>	2.8 x 10 <sup>-5</sup>	8.3 x 10 <sup>-4</sup>	6.6 x 10 <sup>-3</sup>	6.6 x 10 <sup>-8</sup> (NA)	100
226Ra	1.60 x 10 <sup>3</sup>	9.88 x 10 <sup>-1</sup>	7.4 x 10 <sup>-6</sup>	2.3 x 10 <sup>-1</sup>	6.7 x 10 <sup>-1</sup>	6.7 x 10 <sup>-6</sup> (NA)	100
225Ra	4.05 x 10 <sup>-2</sup>	3.92 x 10 <sup>4</sup>	8.1 x 10 <sup>-5</sup>	8.4 x 10 <sup>-4</sup>	6.7 x 10 <sup>-3</sup>	6.7 x 10 <sup>-8</sup> (NA)	100
210Pb	2.23 x 10 <sup>1</sup>	7.63 x 10 <sup>1</sup>	7.0 x 10 <sup>7</sup>	2.4 x 10 <sup>1</sup>	7.2 x 10 <sup>-1</sup>	7.2 x 10 <sup>-6</sup> (NA)	1000
137Cs	3.0 x 10 <sup>1</sup>	8.70 x 10 <sup>1</sup>	7.5 x 10 <sup>7</sup>	2.3 x 10 <sup>4</sup>	2.2 x 10 <sup>-3</sup>	2.2 x 10 <sup>-8</sup> (NA)	1000
135Cs	3.0 x 10 <sup>6</sup>	8.82 x 10 <sup>-4</sup>	2.7 x 10 <sup>2</sup>	2.7 x 10 <sup>2</sup>	2.7 x 10 <sup>2</sup>	2.7 x 10 <sup>-3</sup> (NA)	1000
129I	1.59 x 10 <sup>7</sup>	1.74 x 10 <sup>-4</sup>	3.3 x 10 <sup>1</sup>	3.3 x 10 <sup>1</sup>	3.3 x 10 <sup>1</sup>	3.3 x 10 <sup>-4</sup> (NA)	1000
126Sn	1.0 x 10 <sup>5</sup>	2.84 x 10 <sup>-2</sup>	4.8 x 10 <sup>2</sup>	4.8 x 10 <sup>2</sup>	4.8 x 10 <sup>2</sup>	4.8 x 10 <sup>-3</sup> (NA)	1000
99Tc	2.15 x 10 <sup>5</sup>	1.70 x 10 <sup>-2</sup>	1.3 x 10 <sup>4</sup>	1.3 x 10 <sup>4</sup>	1.3 x 10 <sup>4</sup>	1.3 x 10 <sup>-1</sup>	10,000
93Zr	9.5 x 10 <sup>5</sup>	4.04 x 10 <sup>-3</sup>	1.7 x 10 <sup>3</sup>	1.7 x 10 <sup>3</sup>	1.7 x 10 <sup>3</sup>	1.7 x 10 <sup>-2</sup>	1000
90Sr	2.9 x 10 <sup>1</sup>	1.37 x 10 <sup>2</sup>	5.2 x 10 <sup>7</sup>	1.2 x 10 <sup>4</sup>	6.5 x 10 <sup>-4</sup>	6.5 x 10 <sup>-9</sup> (NA)	1000
59Ni	8.0 x 10 <sup>4</sup>	7.57 x 10 <sup>-2</sup>	3.0 x 10 <sup>1</sup>	3.0 x 10 <sup>1</sup>	3.0 x 10 <sup>1</sup>	3.0 x 10 <sup>-4</sup> (NA)	1000
14C	5.73 x 10 <sup>3</sup>	4.45	1.4 x 10 <sup>2</sup>	1.3 x 10 <sup>2</sup>	1.2 x 10 <sup>2</sup>	1.2 x 10 <sup>-3</sup> (NA)	100

= 7.3 x 10<sup>0</sup>

- (a) 10 years out of the reactor, i.e., the assumed time of emplacement, values from DOE, 1979.
- (b) 300 or 1000 years after closure, i.e., 360 or 1060 years out of reactor, assuming a 50-year operations period before closure; values calculated from (a) and rounded to 2 significant digits.
- (c) 1 x 10<sup>-5</sup> times inventory at 1060 years; from NRC (1983)
- (d) NA means not applicable because curies remaining at 1060 years are less than about 7.3 x 10<sup>-3</sup> Ci, i.e., less than 0.1% of the total release rate limit of about 7.3 Ci/yr; each of these nuclides thus has a release rate limit of 7.3 x 10<sup>-3</sup> Ci/yr.
- (e) Applied 10,000 years after repository closure; from EPA (1984).

2. Reasonably foreseeable releases of radionuclides to the accessible environment shall be less than the quantities calculated according to procedures specified in Table II of 40 CFR 191. This is a proposed EPA containment requirement, 40 CFR 191.13(a) (EPA, 1982; 1984). These limits are shown in the last column of Table 1.
3. Releases of radioactive material to the accessible environment shall conform with generally applicable environmental standards established by the EPA. This is an overall system performance objective of the NRC, 10 CFR 60.112 (NRC, 1983), taken in this report to be the same as the above-listed 40 CFR 191.13(a).
4. Radioactive wastes shall be physically separated from the accessible environment in accordance with the requirements set forth in 10 CFR 60 and 40 CFR 191. This is a DOE system guideline, 10 CFR 960.4.1, taken in this report to be synonymous with the two previously listed requirements.

The three latter requirements, one by each federal agency responsible for regulating nuclear-waste disposal, are restatements of a single requirement, i.e., to comply with performance standards to be set by the EPA. The DOE guidelines for expected postclosure performance (10 CFR 960.4-2-1 through 960.4-2-3) contain three requirements addressing geohydrology, geochemistry, and rock characteristics, respectively. These guidelines restate the requirement to satisfy the postclosure system guideline, 10 CFR 960.4-1, and, by reference, the EPA and the NRC performance standards. Thus, the entire list of regulatory requirements for expected repository behavior addressed in this report reduces to only three topics: groundwater flow time, a release rate

from the engineered barrier system, and cumulative releases of radionuclides to the accessible environment.

Other parts of 10 CFR 60, 40 CFR 191, and 10 CFR 960 list numerous factors that must be considered in assessing expected performance of a repository, but these factors are not requirements. Still other parts of the regulations list requirements, as well as factors to consider, for assessing unexpectedly disrupted long-term conditions, preclosure performance, engineering features, or nonradiological concerns. Because this report is limited to discussion of natural conditions affecting expected long-term radiological performance, these latter concerns are beyond the scope of our intentions and are not addressed.

### 1.3 Organization of the Report

Chapter 2, following this introduction chapter, lists several general assumptions used for our analyses. Chapter 3 summarizes current information about site properties in the context of the proposed DOE technical guidelines for expected postclosure performance. The three pertinent guidelines address geohydrology (Section 3.1), geochemistry (Section 3.2), and rock characteristics (Section 3.3). In Chapter 4, compliance with the applicable NRC and EPA requirements is discussed, drawing from the general site information presented in Chapter 3. It has three sections that separately address the NRC requirements for groundwater-flow time (Section 4.1), limited releases from the engineered barrier system (Section 4.2), and the EPA requirements for limited releases to the accessible environment (Section 4.3). Chapter 5 concludes the report with some observations about how well Yucca Mountain might be expected to comply with current regulations and about the remaining uncertainties that

are the most important to resolve should site characterization of Yucca Mountain be undertaken.

## CHAPTER 2. GENERAL ASSUMPTIONS

Several assumptions are necessary for predicting the expected performance of any repository system. At this time, the site-specific features of the engineered repository have not been determined, nor has the nature of the waste or its exact form. In addition, certain properties and physical mechanisms that occur at Yucca Mountain, but have not been fully determined, must be postulated to allow meaningful analysis of site performance. The broad assumptions listed in this chapter address these topics from the perspective of how they will influence the actual behavior of a repository at Yucca Mountain and, consequently, its prediction. The assumptions are presented early in the report to provide a background for understanding the roles and limitations of the various site features, discussed in Chapter 3, as they might influence site performance, discussed in Chapter 4. These assumptions are also made explicit to allow proper interpretation of the conclusions drawn in Chapter 5. The assumptions are

1. A repository will be located in the lower part of the Topopah Spring Member of the Paintbrush Tuff at Yucca Mountain, along the southwest edge of the Nevada Test Site (NTS) in southern Nevada (Figures 1 and 2). This assumption reflects the current preferred siting option of the DOE for a repository at or near the NTS and is supported by policy decisions based in part on reports detailing site-screening activities (Sinnock and Fernandez, 1982) and evaluations of alternative host rocks (Johnstone et al., 1984).
2. The repository will contain 70,000 metric tons of heavy metal (MTHM) in the form of about 35,000 canisters of spent fuel that will be 10

yr old (i.e., 10 yr after removal from its reactor core) when simultaneously emplaced in the repository. The inventory of waste assumed to be present at the time of emplacement is shown in Table 1.

3. The total area encompassing the waste will be  $6.07 \times 10^6 \text{ m}^2$  (about 1500 acres), yielding an initial thermal-power output of about 12-13  $\text{W/m}^2$  (about 50 kW/acre) (Jackson et al., eds., 1984), assuming that each 10-yr-old MTHM generates about 1.1 kW of thermal power (DOE, 1980).
4. No waste will dissolve or otherwise be removed from the emplacement location until the spent fuel is either 360 or 1060 yr old (or until approximately 300 or 1000 yr after closure of the repository\*), at which times the thermal output of the waste will have decayed to about 0.15 or 0.05 kW/MTHM, equivalent to about 1.75 or  $0.6 \text{ W/m}^2$  (7 or 2.3 kW/acre) (DOE, 1980). This assumption is based on the requirement by the NRC in 10 CFR 60.113(a,1,ii,A) that containment within the engineered system must be essentially complete for at least 300 yr following closure and that complete containment may not be assumed for a greater period than 1000 yr. Thus, in order to build a repository (i.e., receive a license) complete containment for 300 to 1000 yr will be a fact of expected performance. The inventory of waste calculated to be present 300 and 1000 yr after closure of a repository is shown in Table 1.
5. All releases of waste from the repository will be caused by groundwater that flows through the repository and dissolves the spent fuel.

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\* 360 and 1060 yr represent emplacement of 10-yr-old spent fuel, 50 yr of operations through a retrieval period, and 300 and 1000 yr following closure at the end of the retrieval period.

The uranium-oxide matrix of the spent fuel will dissolve at a rate that allows the flowing water to become saturated with uranium. Other radionuclides in the spent fuel will dissolve congruently with uranium on a relative-mass basis. That is, at any given time, the ratio of the mass of uranium to the mass of any other radionuclide will be the same in the spent fuel as it is in the water that is dissolving the fuel.

6. The solubility of uranium will depend on the local geochemical conditions around the waste packages. The conditions around the waste when it begins to dissolve will be similar to those now occurring in the unsaturated zone at Yucca Mountain. This assumption rests in part on assumption 4, which indicated that heat from the repository will have decayed to low levels of output and, therefore, will not significantly affect repository behavior after the 300- or 1000-yr period of complete containment. Accordingly, the solubility of uranium is assumed to remain constant following the containment period.
7. The amount of water available to dissolve and transport waste in the unsaturated zone will be a fraction of the total water moving through the repository level. This fraction will depend on the amount of surface water that infiltrates the earth's surface, the amount of this infiltration that penetrates deeply enough to pass through the repository (i.e., the flux), the total area of the repository, the portion of this area occupied by the underground facilities, the spacing and location of waste canisters within the underground facilities, and the nature of unsaturated flow including the relationship of flow in the rock matrix and in fractures.

8. The flow path from the repository to the accessible environment will be vertically downward through the unsaturated zone to the water table, then horizontally along the water table for 2 or 10 km. These two ends of the flow path are assumed to be alternative boundaries of the accessible environment.
9. Water-flow velocity away from the repository will be equal to the flux divided by the effective porosity of the materials through which flow occurs.
10. The transport velocity of any radionuclide along flow paths away from the repository will be equal to be the water velocity divided by a total retardation factor for that radionuclide in the material through which the water flows. The retardation factor represents the combined effects of radionuclide sorption, mineral precipitation, and any other mechanism, such as diffusion, that will slow the net migration of waste species.
11. The decay of radionuclides in time and the resulting accumulation of daughter products are assumed to occur in a manner described by a system of equations, first developed by Bateman (1910), allowing five members of each decay chain to be considered. For the neptunium series Pu-241, Am-241, and Ra-225 are assumed to remain in secular equilibrium with their parent species. Similarly, for the uranium series Pu-238, Am-242, Cm-242, Pb-210, and Ra-226 are assumed to remain in secular equilibrium with their parent species. For the actinium series Np-239 is assumed to remain in secular equilibrium with its parent species. All fission products are treated as single-member chains. Table 1 shows the initial inventory assumed to be

present in 10-yr-old spent fuel and the calculated inventories after the radionuclides have decayed for 360 and 1060 yr.

Given the general assumptions and boundary conditions listed above, it is not necessary to use sophisticated groundwater flow models or complex contaminant-transport equations to estimate radionuclide transport times and amounts at a repository site. On the contrary, the assumptions enable a simple, conservative investigation of the proper bounds to place on the expected performance of a repository at Yucca Mountain. In Chapter 4, the bounds are established under a range of values for several critical site conditions. Ancillary assumptions are necessary for determining the appropriate values or ranges of values for these site conditions, including groundwater flux, sorption coefficients, uranium solubility, and others. The basis for these latter assumptions will be made explicit in the following sections. Finally, specific assumptions are necessary to support the definitions of regulatory terms such as "disturbed zone," "engineered barrier system," "accessible environment," and others, as well as about the specific geometrical arrangement of repository facilities. These assumptions will be made at the appropriate places in Chapter 4 where they can be clearly tied to the calculations of performance.

A word of caution is in order. The conclusions in this report are based on current information about Yucca Mountain. Much of this information is preliminary. It is commonly limited in terms of either statistical reliability or understanding of the physical mechanisms that act through the site properties. Future investigations at Yucca Mountain or studies about nuclear-waste disposal in general may reveal flaws in the data, assumptions, or

analysis techniques used in this report. To reduce the potential for misinterpretation or misrepresentation of site behavior, we have used and identified, wherever possible, conservative assumptions and analysis techniques, i.e., those that tend to err on the side of more deleterious predictions. We have also included calculations based on ranges of values for site properties wherever uncertainty is great or where the calculations are particularly sensitive to the assumed ranges in values. This paper should not be taken as a definitive analysis of the capability of the Yucca Mountain site to meet regulatory requirements. It should be interpreted only as a means to place the strengths and weaknesses of the site in proper perspective. In this spirit we hope this report will aid the making of impending decisions about whether an investment in extended site characterization is justified and, if characterization is begun, about the data that are most critical to gather for ensuring compliance with the applicable regulations for expected long-term repository performance.

## CHAPTER 3. SITE CONDITIONS

This section outlines the known and assumed physical conditions relevant for assessing the expected postclosure performance of a repository at Yucca Mountain. It is divided into three subsections addressing, in order, geohydrology, geochemistry, and rock characteristics. These three topics correspond to the three proposed siting guidelines of the DOE for expected postclosure conditions and processes (DOE, 1983). Because the guidelines have not been published as a final rule, they are subject to change. For the version current at the time of this writing each guideline lists a qualifying condition and several favorable and potentially adverse conditions. In the guideline for geohydrology a disqualifying condition is also listed, as described in Section 1.2. We do not attempt to argue whether Yucca Mountain qualifies under each guideline, nor do we specifically discuss whether the site has any of the favorable or potentially adverse conditions corresponding to each guideline. Chapter 4, which addresses the NRC and EPA requirements, presents analyses that can be used to determine whether the site satisfies the intent of the guidelines for these three topics. This chapter uses the proposed siting guidelines solely as an organizing principle for discussing the data and associated assumptions about the physical conditions at Yucca Mountain, deferring to the following chapter the analyses needed to judge whether the site may be expected to comply with regulatory requirements.

### 3.1 Geohydrology

The movement of water through a repository site is important for two basic reasons, it sets an upper limit on how much waste can be dissolved within a repository and how rapidly wastes can migrate in solution toward the

accessible environment. The hydrologic conditions at Yucca Mountain needed for analyses of repository behavior are, therefore, those that will influence the dissolution of emplaced waste and the movement of waste with groundwater between the repository and the accessible environment. At Yucca Mountain these conditions are determined in large part by relationships between the hydrologic characteristics of the rocks along the flow paths and the amount of water moving through the mountain. To address these relationships, this section first outlines the general stratigraphic and structural features of the rocks at Yucca Mountain (Section 3.1.1), and then discusses the amount of water expected to move through the various rock units and structures (Section 3.1.2). Finally, these two topics are combined under the dictates of Darcy's law as extended to unsaturated flow to outline the manner in which the water flux will move through the Yucca Mountain environment (Section 3.1.3). Separate subsections address flow behavior in the unsaturated zone (Section 3.1.3.1) and the saturated zone (Section 3.1.3.2).

### 3.1.1 Stratigraphic and Structural Setting

The general hydrogeologic stratigraphy of Yucca Mountain and its relation to groundwater flow paths are shown in Figure 3. Six general hydrogeologic units are distinguished by their flow characteristics. They are, from top to bottom: the densely welded Tiva Canyon unit, the nonwelded Paintbrush unit, the densely welded Topopah Spring member, the nonwelded vitric Calico Hills unit, the nonwelded zeolitic Calico Hills unit, and the older tuff unit. Tables 2 and 3 summarize the hydrologic characteristics of these units.

The densely welded Tiva Canyon unit is the caprock at Yucca Mountain and is densely fractured (Table 3). Its matrix-saturated hydraulic conductivity is very low, on the order of 1 mm/yr. Bulk porosity is about 10%. Effective

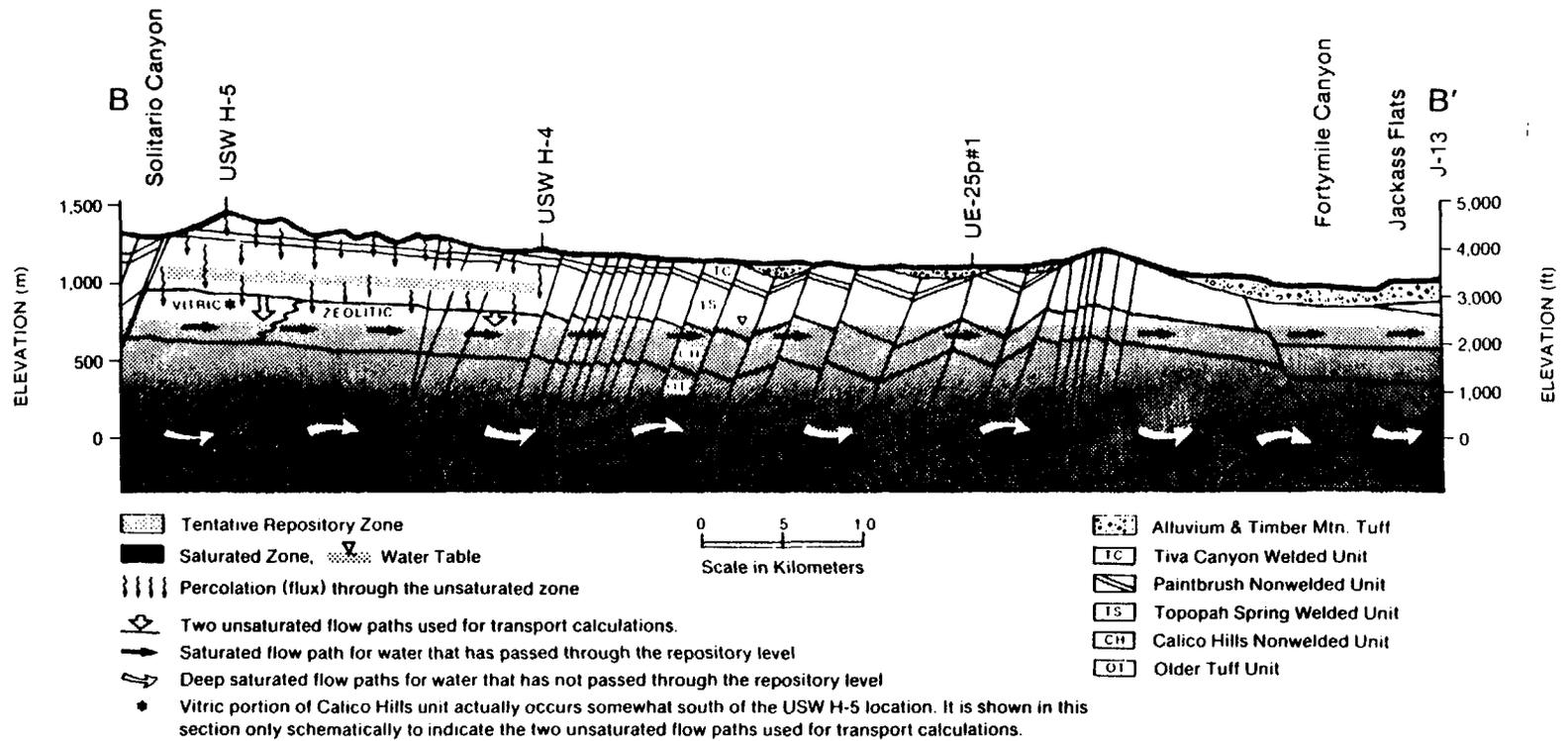


Figure 3. General hydrogeologic cross section of Yucca Mountain showing the anticipated flow paths from a potential repository to the water table and along the top of the saturated zone toward the accessible environment; UE-25p#1, USW H-4, and USW H-5 denote boreholes used for stratigraphic and water table control points; see Figure 6 for location of the section line.

Table 2. Relation of stratigraphic and hydrogeologic units at Yucca Mountain.

STRATIGRAPHIC UNIT		HYDROGEOLOGIC UNIT	APPROXIMATE THICKNESS (METERS)	COMMENTS
Alluvium		Alluvium	0-30+	Underlies washes; thin layer on flats.
Tiva Canyon Member		Tiva Canyon welded unit	70-150	Densely to moderately welded caprock that dips 5-8° eastward at Yucca Mountain; high fracture density.
Paintbrush Tuff	Pah Canyon Member	Paintbrush nonwelded unit	0-200	Vitric, nonwelded, porous, poorly indurated, bedded in part; low fracture density.
	Yucca Mtn. Member			
	Topopah Spring Member			
Paintbrush Tuff	Topopah Spring Member	Nonwelded	Topopah Spring welded unit	Densely to moderately welded; several lithophysal (cavity) zones; high fracture density; central and lower part is candidate host rock for repository.
		Vitrophyre Welded Vitrophyre		
		Nonwelded		
Tuffaceous Beds of Calico Hills	Zeolitic	Calico Hills nonwelded unit	100-400	Base of unit is determined by the water table; vitric in southwest Yucca Mountain, zeolitic in east and north.
Crater Flat Tuff	Prow Pass Member	Nonwelded	Older tuffs	In USW H-1, lower part has hydraulic head about 50 m higher than water table at USW H-1.
		Welded		
	Bullfrog Member			
	Tram Member			
Lava		Older tuffs	> 1200 m	In USW H-1, lower part has hydraulic head about 50 m higher than water table at USW H-1.
Lithic Ridge Tuff				
Older Volcanics				
Pre-Tertiary Rocks		Pre-Tertiary Rocks	Unknown	Silurian carbonate occurs 2.5 km east of proposed repository at depth of 1,250 m in UE-25p#1 where hydraulic head is about 20 m higher than water table.

Table 3. Inferred hydrologic properties of the matrix and fractures of the hydrogeologic units at Yucca Mountain.

HYDROSTRATIGRAPHIC UNIT	MATRIX PROPERTIES						
	Estimated Bulk Porosity (% ± 1)	Saturated Effective Porosity (%)	Average Saturated Hydraulic Conductivity (cm/sec)	Average Saturated Hydraulic Conductivity (mm/yr)	Saturation (% of Bulk Porosity ± 1)	Approximate Matric Potential (cm)(19)	Approximate Effective Hydraulic Conductivity (mm/yr)(20)
Tiva Canyon Densely Welded	10 ± 5.3(1)	5-8	2.5 x 10 <sup>-9</sup> (7)	0.8	72(13)	-10,000	0.025
Paintbrush Nonwelded	45 ± 11.8(2)	20-30	2.4 x 10 <sup>-6</sup> (8)	760	56 ± 17(14)	-8,000	150
Topopah Spring Densely Welded	15 ± 5.1(3)	8-12	3.5 x 10 <sup>-9</sup> (9)	1.1	69 ± 15(15)	-20,000	0.05
Calico Hills (Vitric)	39 ± 7.7(4)	20-30	1.3 x 10 <sup>-6</sup> (10)	410	NA(16)	--	--
Calico Hills (Zeolitic)	30 ± 8.6(5)	10-20	4.2 x 10 <sup>-9</sup> (11)	1.3	92 ± 5(17)	-20,000	0.05
Older Tuffs	23 ± ? (6)	5-15	1.1 x 10 <sup>-7</sup> (12)	35(12)	89 ± 8(18)	NA	35

- (1) average of 11 samples
- (2) average of 15 samples
- (3) average of 51 samples
- (4) average of 4 samples
- (5) average of 27 samples
- (6) average of 67 samples
- (7) log average of 10 samples; 3 samples tested at lower limit of apparatus
- (8) log average of 6 samples; 1 sample tested at lower limit of apparatus
- (9) log average of 22 samples; 1 sample tested at lower limit of apparatus
- (10) log average of 5 samples

- (11) log average of 17 samples; 4 samples tested at lower limit of apparatus
- (12) log average of 33 samples, unit is saturated, fracture flow dominates
- (13) only 1 sample available
- (14) 5 samples
- (15) 27 samples
- (16) no data available
- (17) 5 samples
- (18) 14 samples; unit is beneath the water table and therefore saturated though some small pores may not allow water to enter, low saturation may also indicate measurement bias
- (19) representative samples used; from Peters (1984)
- (20) representative samples used; from Peters and Gauthier (1984)

Table 3 (continued)

HYDROSTRATIGRAPHIC UNIT	FRACTURE PROPERTIES						
	Approximate Density (per m <sup>3</sup> )(21)	Bulk Saturated Hydraulic Conductivity (mm/yr)	Calculated Effective Aperture (microns)(26)	Calculated Effective Fracture Porosity (%)(27)	Calculated Aperture(μ)(28) Required to Pass a Flux of		
					1 mm per/yr	5 mm per/yr	10 mm per/yr
Tiva Canyon Densely Welded	20	365,000(22)	89	0.0018	1.2	2.1	2.7
Paintbrush Nonwelded	10	75,000(23)	66	0.0007	1.6	2.7	3.4
Topopah Spring Densely Welded	40	365,000(24)	71	0.0028	1.0	1.7	2.1
Calico Hills (Vitric)	5	75,000(24)	83	0.0004	2.0	3.4	4.6
Calico Hills (Zeolitic)	5	75,000(25)	83	0.0004	2.0	3.4	4.6
Older Tuffs	5-20	75,000 - (25) 365,000	83-89	0.0004- 0.0018	NA	NA	NA

- (21) From Scott et al. (1983) rounded to nearest 5  
 (22) Assumed equal to saturated Topopah Spring  
 (23) Assumed equal to Calico Hills and Older Tuffs  
 (24) Representative value from well J-13 (Thordarson, 1983)  
 (25) Representative value from well J-13 (Thordarson, 1983), H-1, (Barr, 1984)  
 (26) Aperture,  $b = (12ps)^{0.333} \times 10^6$ ,  $s =$  distance between fractures in meters obtained from one divided by fracture density,  $p =$  permeability in m<sup>2</sup> or  $3.2 \times 10^{-18}$  times conductivity in mm/yr (from Freeze and Cherry, 1979)  
 (27) Calculated effective porosity = fracture density x aperture in microns x  $10^{-6}$   
 (28) Assume all fractures participate in flow where permeability =  $3.2 \times 10^{-18}$  times flux in mm/yr, and aperture is calculated as per note 26

matrix porosity is probably somewhat less, even under saturated conditions (Thordarson, 1983). This unit occurs entirely above the water table, and saturation is estimated as about 75% on the basis of laboratory measurements of core samples (Table 3).

The underlying nonwelded Paintbrush unit is less densely fractured and has a matrix-saturated hydraulic conductivity of several millimeters per year. Bulk porosity is very high, about 45%, and effective porosity is probably also high relative to the densely welded units. Saturation of this unit is apparently about 55% based on laboratory measurements of core samples (Table 3).

The tentative host rock for a repository at Yucca Mountain is the next lower unit, the densely welded Topopah Spring unit (Table 2). It is densely fractured and has a low matrix-saturated hydraulic conductivity, nearly identical to that of the densely welded Tiva Canyon unit. Bulk porosity is about 15%, and effective matrix porosity is assumed to be about 10%. Saturation, based on both field and laboratory measurements, appears to be about 70% (Table 3). It is the deepest stratigraphic unit completely above the water table in the potential area of waste emplacement. The lower part of this unit is beneath the water table in restricted locations several kilometers east of the Yucca Mountain site.

The nonwelded Calico Hills unit underlies the target host rock. It is divided into two distinct subunits, vitric and zeolitic (Tables 2 and 3). Though the two subunits occur at the same stratigraphic level (Figure 3), they are considered distinct hydrogeologic units because they have significantly different capabilities to transmit water through the rock matrix. The vitric part occurs beneath the southwest portion of the potential emplacement area and has hydrologic properties similar to those of the nonwelded Paintbrush unit, i.e., low fracture density and high saturated hydraulic conductivity

(Table 3). The zeolitic part occurs beneath the north and east portions of the potential emplacement area and has low fracture density, similar to that of the vitric part and the nonwelded Paintbrush unit, and low matrix-saturated hydraulic conductivity, similar to that of the densely welded units. Bulk porosity is generally high, 30% to 40%, throughout the Calico Hills units, though perhaps somewhat higher in the vitric unit than the zeolitic unit. Effective porosity is assumed to be about 20% to 30% in the vitric unit and 10% to 20% in the zeolitic unit (Table 3). Both units appear to be nearly saturated. The water table at Yucca Mountain generally occurs within the Calico Hills unit.

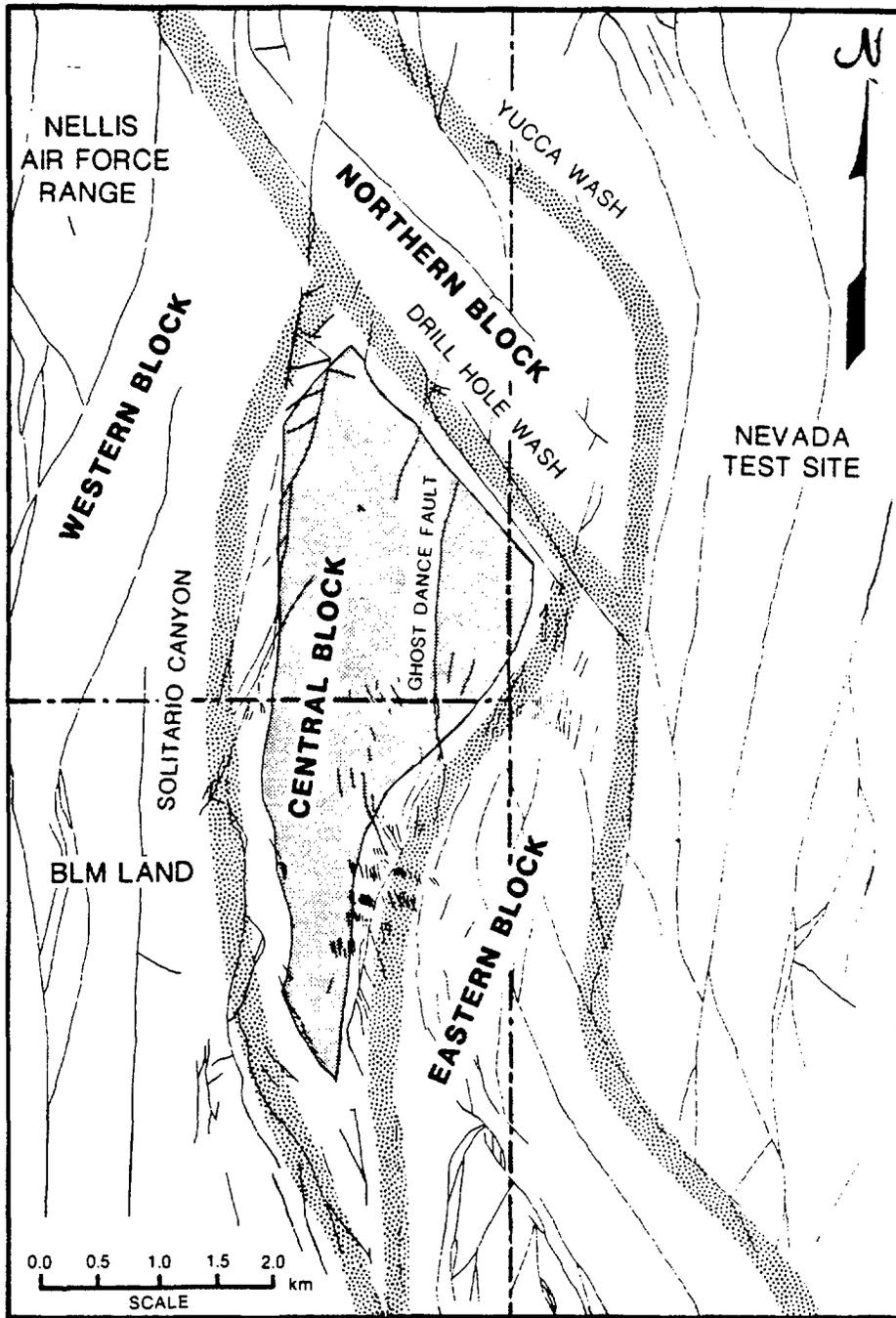
The lowermost unit in the flow system between the proposed repository and the accessible environment is designated as older tuff. It occurs exclusively beneath the water table throughout the Yucca Mountain site. Its top corresponds to the uppermost, moderately to densely welded layers in the Prow Pass or Bullfrog Members of Crater Flat Tuff (Table 2). It is slightly to densely fractured, and matrix hydraulic conductivities generally fall between those of densely welded and nonwelded units. Bulk porosity is about 25%. Because this unit is entirely below the water table, it is fully saturated (Table 3).

Local variation of hydrologic properties within each of the units is certain. These variations influence the details of local flow, but site characterization to date is not sufficient to reliably map them. Future characterization will decrease, but not eliminate, uncertainty about the distribution of heterogeneity within each unit. However, intraunit variations are almost certainly less influential on general flow conditions than variations among units because the differences of properties within units are much less than the differences among units. For this reason, we conclude that the gross behavior of the flow system can be reasonably approximated by assuming uniformity within each hydrogeologic unit.

The structural environment at Yucca Mountain may strongly influence groundwater flow through each of the units, particularly if the amount of flux through the unsaturated zone is large enough to cause flow through fractures. Accordingly, the structural features of primary interest are related to the distribution, density, orientation, and size of fractures throughout the site. The fractures in turn, are strongly related to the block-faulted nature of the Yucca Mountain area and to the degree of welding of the stratigraphic units.

Major faults, with up to a few hundred meters of vertical offset, have created a series of east-tilting blocks, hundreds to thousands of meters wide and several kilometers long (Figure 4). The reference emplacement area is within the informally designated central block (Figure 4), which dips eastward about 5° to 8°. This block is bounded on the west by a large fault zone along Solitario Canyon. To the east, it is bounded by several smaller, closely spaced faults or fracture sets. The northern edge is defined by Drill Hole Wash, an informally named canyon along a zone of possible strike-slip faulting or dense fracturing. The southern boundary is less well defined, but generally occurs where the east- and west-bounding fault zones converge sufficiently to make the block too narrow for practical extension of emplacement drifts. Several minor faults with little vertical offset occur within the central block. The largest is informally named the Ghost Dance Fault (Figure 4). It has a maximum displacement of about 15 m near its central point and diminishes to no offset within a few hundred meters to the north and south.

The major block-forming faults surrounding the site generally trend just east of north and may serve as preferential groundwater flow conduits, particularly for horizontal flow in the saturated zone and perhaps for vertical flow in the unsaturated zone. Fractures observed at the surface trend predominantly north to northwest (Scott et al., 1983). The density of fractures



-  Generalized outlines of structural blocks
-  Tentative location of underground repository
-  Surface location of exposed and inferred faults

Figure 4. Major, informally designated structural blocks at Yucca Mountain and their relation to individual faults exposed in the ranges and inferred where buried by alluvium.

generally increases with the degree of welding and is probably somewhat uniform within each structural block for each stratigraphic unit. Near major faults and local areas of abundant small faults, fracture densities probably increase. As with intraunit stratigraphic variations, the influences of local variations in fracture density probably can be ignored because the effects of major structures and stratigraphic distinctions dominate the general flow conditions at the site.

### 3.1.2 Groundwater Flux

Water that infiltrates at the surface and percolates through the stratigraphic and structural fabric of the site determines the unsaturated flow environment at Yucca Mountain. The amount of deep infiltration (unsaturated flux) is one of the most important and favorable aspects of Yucca Mountain, when considered as a repository site. Because the repository, if built, would be situated in the unsaturated zone, the total amount of water available to dissolve and transport the waste is limited to the amount of deep infiltration from the surface.

Several approaches are available to estimate the amount of unsaturated flux. The first is based on information about climatic conditions, vegetation, topography, and soil conditions. Under this approach, infiltration is calculated by subtracting the amount of surface runoff plus evapotranspiration from the amount of precipitation, which increases with elevation in southern Nevada. Soil conditions, topography, temperature, humidity, and vegetation are used to estimate runoff and evapotranspiration throughout the year. Based on this method, Rice (1984) estimated that infiltration for a large region

surrounding Yucca Mountain is less than 0.1 inch (~2.5 mm)\* per year, though the study area was not small enough to indicate how much less occurs at Yucca Mountain.

Several investigators have used a similar, though perhaps less formal, approach which combines considerations of the mass balance between recharge and discharge in groundwater basins (water budgets) with assumptions about the locations of recharge based on elevation-determined climatic conditions. Using this approach, Eakin and others (1963), Walker and Eakin (1963), Mifflin (1968), and Waddell (1982) assumed that no recharge occurs at Yucca Mountain or in similar, nearby climatic zones. Rush (1970) used a method devised by Eakin and others (1951) to estimate that less than 3% of the precipitation in the Yucca Mountain region infiltrates deeply enough to recharge the saturated zone at elevations less than 5000 ft (~1500 m). Blankenagle and Weir (1973) used the same method to arrive at an estimate that only 2% of the precipitation in the 6000- to 7000-foot (~1800- to 2100-m) elevation range at Pahute Mesa percolates deeply enough to recharge the saturated zone. Rush's approach (Rush, 1970) provides the more conservative basis for establishing an upper bound for recharge of about 4 mm/yr for the 1200- to 1500-m elevation range at Yucca Mountain, where precipitation is estimated by Quiring (1965) to be about 6 to 8 in/yr (~150 to 200 mm/yr) (i.e., recharge is somewhat less than 4.5 to 6.0 mm/yr). On the basis of water-budget evaluations of the regional flow system, Rush assumed, along with Waddell and the others mentioned above, that the actual quantity of recharge in acre feet from this elevation zone was negligible.

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\* Metric units are generally used in this report unless the original data from previous studies are being described; in these cases metric conversions are provided.

The water-budget considerations of all these investigators indicate that no recharge is required from Yucca Mountain or similar climatic environments to explain the overall behavior of the regional flow system. We conclude that reasoning based on climatic information in combination with water-budget considerations indicates an upper bound of a few millimeters per year for the flux through the unsaturated zone at Yucca Mountain.

Two other approaches to estimating unsaturated flux are based directly on site-specific information. One infers vertical flux from measurements of the geothermal gradient, the variation of temperature with depth; the other infers flux from moisture contents and hydraulic pressures in rocks from the unsaturated zone. Using the geothermal approach, Sass and Lachenbruch (1982) estimated that water is moving downward at a rate of 1 to 10 mm/yr in the lower unsaturated zone and upper saturated zone at borehole USW G-1 in Drill Hole Wash. For shallow holes that penetrate only the upper portion of the unsaturated zone beneath Drill Hole Wash, geothermal data suggest a negative (upward) flux of up to tens of millimeters per year. These estimates are based on assumptions about the local geothermal flux and generalized data for the thermal conductivity of the stratigraphic units. Given the uncertainties due to the assumptions and generalizations, combined with the range of estimated flux for different locales, this method is currently unable to determine local flux within a narrow range. However, the geothermal approach does provide independent estimates of recharge that strengthen evidence that it is very low, certainly less than 10 mm/yr and probably less than 1 mm/yr.

The final approach to estimating flux through the unsaturated zone is based on measurements of moisture contents, hydraulic pressures, and effective hydraulic conductivities of rocks along unsaturated flow paths. This approach

provides the most direct evidence about unsaturated water flux. For unsaturated material, openings exert a pull or suction on water which is inversely proportional to the size of the openings. This suction is due to capillary or surface-tension forces. These forces create negative pressures that tend to draw water into the rock matrix and hold it there. The lower the saturation or the less water there is in a rock of a given porosity, the greater is the capillary suction, because at lower saturations smaller voids with stronger capillary pull exert the negative pressure. Therefore, effective hydraulic conductivity also decreases as saturation decreases.

Measurements on core from Yucca Mountain indicate that saturation of the potential host rock, the Topopah Spring Member, is about 70% (Blair et al., 1984). Substantiating evidence currently is being obtained from in situ pressure-head measurements of -20 to -40 bars (about -20,000 to -40,000 cm of water) for the Topopah Spring Member in hole USW UZ-1 at Drill Hole Wash just north of the target emplacement area (P. Montezar, USGS, personal communication). These suction pressures correspond to saturations of less than about 50% to 80% based on moisture content-pressure head relations determined from core samples by Blair and others (1984) (Figure 5). The corresponding hydraulic conductivities are of the order of 0.01 to 0.1 mm/yr (Figure 5), indicating that 0.5 mm/yr constitutes a conservative upper limit on the flux through the rock matrix at the repository level (Peters, 1984).

Because the Topopah Spring Member is fractured, it is possible that some of the flux moves through fractures in the unsaturated zone. Two lines of evidence show, however, that this is unlikely. First, calculations by Travis and others (1984) indicate that water moving through fractures with apertures as small as 100  $\mu\text{m}$  would be unable to penetrate more than a few meters, at most, through fractured, densely welded tuff with matrix saturations as high

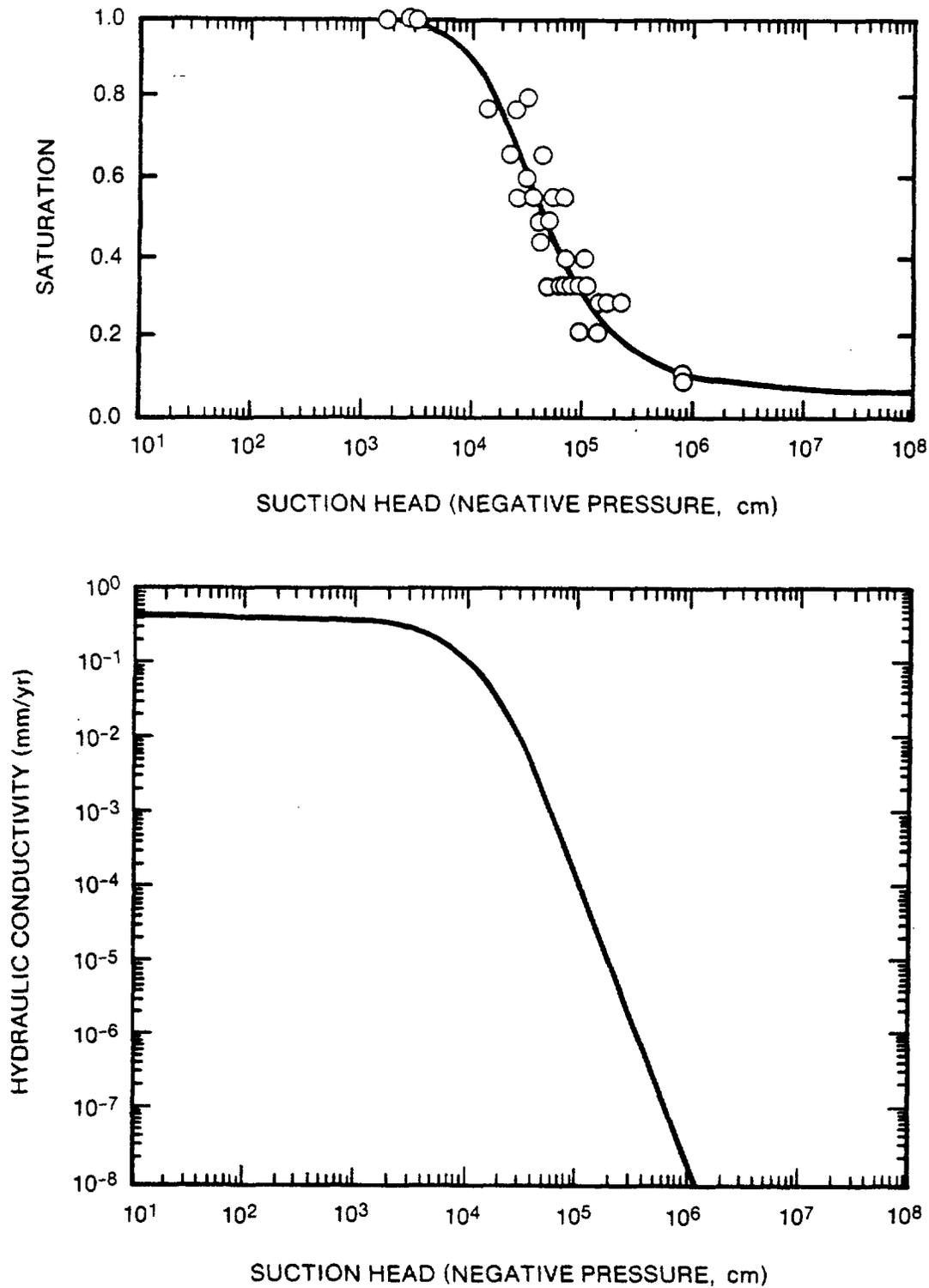


Figure 5. Relations between saturation, hydraulic conductivity, and suction head; bottom curve (from Peters and Gauthier, 1984) calculated from best-fit upper curve (from Peters, 1984); upper curve generated from measurements represented by circles (from Blair et al., 1984) of a representative sample (G4-6) of the Topopah Spring welded unit.

as 90%, and it would penetrate even shorter distances for lower saturations or smaller fracture apertures. Under matrix suction pressures corresponding to saturations of 90% or less, all water in the fractures would be drawn into the rock as the water moved short distances through the fractures. Wang and Narasimhan (1984) calculate a pressure range over which the transition from fracture flow to matrix flow would occur in jointed blocks composed of densely welded tuff. They predict the transition will occur abruptly at negative matrix pressures of about a few tens of centimeters of water, far higher than the observed pressures at Yucca Mountain. The hydraulic conductivity (the same as effective flux, given a gradient of 1) corresponding to the calculated pressure threshold for fracture flow is about 0.5 to 1 mm/yr. The calculations by Travis and others (1984) and Wang and Narashimhan (1984) indicate that the low moisture contents observed in the host rock will prohibit any sustainable flow through the fractures in the unsaturated zone.

The second line of evidence is provided by Peters and Gauthier (1984), who calculate that flux in excess of about 0.5 mm/yr would nearly saturate most rocks in the unsaturated zone at Yucca Mountain, including the Topopah Spring Member. If the rocks were initially of low saturation and sustained fracture flow were to occur, water drawn from the fractures into the matrix would completely saturate the matrix under a flux of about 0.5 mm/yr. Thus, according to Peters and Gauthier (1984), a flux in excess of about 0.5 mm/yr would produce a higher moisture content and lower suction pressure than the values observed at Yucca Mountain. Only if higher moisture contents and lower suction pressures were to occur would the fractures be able to sustain water flow, as pointed out by Travis and others (1984) and Wang and Narashimhan (1984).

than the upper end of the range estimated from more indirect climatic, water-budget, or geothermal methods. Before this conceptual model of flux through the unsaturated zone can be firmly established, however, more widely distributed data are needed for in situ moisture contents, pressure heads, and hydraulic conductivities.

After water percolates vertically to the water table, it will mix with the water flowing into the site as underflow from recharge regions to the north. This underflow or flux through the saturated zone at Yucca Mountain has been estimated by Waddell (1982) to be on the order of  $10^{-5}$  to  $10^{-6}$   $m^3/s$  for a 1-m-wide strip of saturated aquifer (Sinnock et al., eds., 1984). For a spot location at the northern end of the potential repository area, Waddell (1982) calculated a flux of about  $2 \times 10^{-6}$   $m^3/s/m$  per meter of aquifer width; for a spot location just southeast of the site, the calculated value is about  $5 \times 10^{-7}$   $m^3/s/m$ . Waddell (1982) assumes all flux enters the site as underflow from recharge areas to the north, primarily at Pahute Mesa. Though considerable uncertainty is associated with these estimates because of the regional scale of the model that produced them, they are the only ones available and are presented here without further discussion. In the next section, the implications of these estimates are discussed with respect to attempts to estimate hydraulic conductivities in the saturated zone.

### 3.1.3 Groundwater Flow at Yucca Mountain

As outlined in Chapter 2, assumption 9, the velocity of water flow,  $V_w$ , in both the saturated and unsaturated zones is assumed to obey general Darcy principles, so the velocity is equal to the flux,  $F$ , divided by the effective porosity,  $n$ :

$$V_w = F/n \quad (1)$$

Concentrations of infiltration in time or space may seem to provide a means of supplying enough flux to cause fracture flow in limited portions of the site. This may seem particularly likely beneath the washes which concentrate runoff and, hence, moisture available for infiltration along or across fault zones or other densely fractured locations. However, a logical consequence of this situation would be a horizontal pressure gradient away from the limited zones of fracture flow and the adjacent, nearly saturated rock toward zones where no fracture flow occurs and the rock matrix is less saturated. It is unlikely, though not certain, at this time, that such a gradient could be maintained for very long, because the pore water would tend to migrate along the gradient through the matrix in an attempt to establish an equilibrium pressure that would eliminate the gradient. Given this reasoning, we tentatively conclude that pulses of flux through fractures at restricted places are not very likely, at least not as episodic events occurring at regular and frequent intervals at the same place. This conclusion needs to be confirmed by detailed modeling that calculates the lateral gradients of moisture content and pressure, if any, that can be sustained by local pulses of fracture flow of various intensities and frequencies.

At the current time, data on moisture content in the unsaturated zone strongly indicate that sustained, widely distributed fracture flow is not a credible process at Yucca Mountain. As a result, the average flux is probably limited to a value equal to the hydraulic conductivity of the matrix under the suction heads of 20,000 to 40,000 cm, corresponding to saturations of 85% or less. Though these values are not yet firmly established for all hydrogeologic units and undoubtedly vary within the units, the current data on hydraulic conductivities indicate that the average flux through Yucca Mountain is probably less than about 0.5 mm/yr, or about an order of magnitude less

In the unsaturated zone,  $n$  is determined by the moisture content and degree of saturation of the rocks. This flux cannot exceed, but may be less than, the amount determined by the general Darcy equation

$$Q = K \cdot \frac{\partial h}{\partial l} \cdot A \quad (2)$$

where  $Q$  is the total volumetric rate of flow,  $K$  is the hydraulic conductivity,  $\partial h/\partial l$  is the hydraulic gradient, and  $A$  is the cross-sectional area through which flow occurs.\* The flux is the same as  $Q$  for a unit area of the total area,  $A$ .

#### 3.1.3.1 Flow in the Unsaturated Zone

A flow system tends to adjust the basic flow parameters in a manner that enables the flux to be transmitted. In contrast to the saturated zone where the gradient generally adjusts to a minimum slope required to ensure that the flux is transmitted through various rocks, with a differing but fixed conductivity, the conductivity of a given rock in the unsaturated zone will tend to adjust to the minimum value required to transmit the flux under a gradient fixed by gravity at unity. This can occur because conductivity changes as the saturation changes, so, in effect, moisture contents will adjust to yield a conductivity equal to the flux, given a gradient of 1.

Two types of hydraulic conductivity, matrix and fracture, are pertinent to understanding water flow through the unsaturated rocks at Yucca Mountain.

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\* Conventionally,  $\partial h/\partial l$  is taken to be a negative number because flow occurs from points of high to low head; for convenience we assume  $\partial h/\partial l$  is positive and omit the minus sign from the Darcy equation.

If the flux exceeds the matrix conductivity times the gradient, flow will be through fractures, which at Yucca Mountain generally have much higher conductivities and much lower effective porosities than the matrix (Table 3). Because effective porosities of fractures are generally low, velocities in fractures tend to be relatively rapid. The upper limit of matrix conductivity is set by its value under saturated conditions. The saturated matrix conductivity of the Tiva Canyon, Topopah Spring, and zeolitic Calico Hills units is about 1 mm/yr (Table 3). If flux is less than the saturated matrix conductivity, water will tend to flow relatively slowly through the high effective porosity of the matrix. It follows that flux through the unsaturated zone at Yucca Mountain in excess of the saturated matrix conductivity (gradient = 1) must pass through fractures, so that flux in excess of about 1 mm/yr would tend to cause fracture flow through the densely welded Tiva Canyon and Topopah Spring units and the nonwelded, zeolitic Calico Hills unit.

However, this excess flux would probably never exceed a few millimeters per year at Yucca Mountain, averaged in time and space. The fractures in the densely welded units and zeolitic Calico Hills unit have a capacity to annually transmit tens of thousands of millimeters of water (Table 3). As a result, the relatively low flux in excess of the matrix capacity, were it to occur, would occupy only a small portion of the total fracture network, probably that portion composed of the narrowest interconnected apertures required to transmit the water (Table 3, last three columns). It is plausible that the small fractures participating in the flow for such small excess flux would behave more like pores in the matrix than the large fractures required to transmit a large flux in, for example, a saturated flow system. If the capillary forces in matrix pores and small fractures were similar, exchange of water between the two could occur, and the fractures would constitute an

extension of the effective porosity of the matrix necessary to establish a conductivity just sufficient to pass the flux by "porous" flow. As a result, effective porosity may not drop precipitously, and may even increase slightly, upon initiation of fracture flow.

Flux necessary to initiate fracture flow, i.e., greater than about 1.0 mm/yr, is unlikely, as discussed in Section 3.1.2, because of the apparent low saturation and corresponding effective conductivity of the Topopah Spring Member. The preliminary nature and sparse distribution of saturation and conductivity data do not allow complete dismissal of a higher flux, at least in portions of the site not tested for saturation values. Even for the unlikely event where flux exceeds the carrying capacity of the matrix of the densely welded and zeolitic units, the nonwelded, nonzeolitic units, with matrix conductivities of several hundred to a thousand millimeters per year, could pass the water through pores in the matrix, thereby precluding significant fracture flow through these units.

If the climate were to change to wetter, pluvial conditions similar to those about 15,000 yr ago, more infiltration might occur, and water might be able to pass through the fractures after saturating the matrix. Based on the interpretation of fossil-plant remains from pack-rat middens, Spaulding (1983) reasons that pluvial climates at Yucca Mountain were similar to these now occurring 1000 or 2000 ft higher, analogous to the present climate on Pahute Mesa. Blankenagel and Weir (1973) estimate that 2% of precipitation or about 1400 acre-ft ( $\sim 1.7 \times 10^6 \text{ m}^3$ ) of recharge occur there annually in the 6000- to 7000-foot ( $\sim 1800$ - to  $2100$ -m) elevation range over an area of 95,000 acres ( $\sim 3.8 \times 10^8 \text{ m}^2$ ). This is equivalent to an average flux of about 4.5 mm/yr. Rush (1970) estimates recharge in the 6000- to 7000-foot ( $\sim 1800$ - to  $2100$ -m) elevation zone to be 7% of precipitation, which Quiring (1965) estimates to be

about 8 to 12 in/yr (200 to 300 mm/yr), yielding a flux of about 14 to 21 mm/yr. This information leads us to a preliminary conclusion founded on conservative estimates that no more than 10 or 20 mm/yr of flux would be available to pass through the unsaturated zone at Yucca Mountain under wetter climates.

However, high, past flux implies certain logical consequences that may constrain estimates of the effects of pluvial conditions on flux at Yucca Mountain. If flux through the unsaturated zone were more than a few millimeters per year during the last pluvial episode, which lasted several decamillenia and ended about 10,000 to 12,000 yr ago (Spaulding, 1983), the matrix of the rocks would have been nearly saturated because of the principles discussed above. When the pluvial climate ended and infiltration slowed, the rock matrix would have drained by matrix flow to the level of saturation observed today. Given the low matrix conductivity and thickness of the densely welded units, such a draining process (from nearly 100% to 85% or less saturation) may have required more time under a prevailing flux than has been available since the end of the last pluvial episode. Detailed modeling of this drainage problem at Yucca Mountain has not been undertaken, but it must be considered when attempting to establish the likely change in flux through the unsaturated zone due to the potential onset of another pluvial climate.

Thus, the velocity of flow through the unsaturated zone and the corresponding water travel times at Yucca Mountain depend heavily on the flux caused by deep infiltration. If it is less than about 0.5 mm/yr, the most likely case, flow probably will be exclusively through the pores of the rock matrix, and travel times through all units will be very long. If the current flux is higher than presently thought or if it were to increase in the future, movement of water through the unsaturated zone might occur by both fracture

and matrix flow. The north and east portions of the waste-emplacment area are underlain by the zeolitic Calico Hills unit, and flow to the water table in those portions probably would be almost entirely by rapid fracture flow for flux in excess of about 1 mm/yr. Flow time in the south and west portions of the emplacment area would be dominated by slow flow through the matrix of the vitric Calico Hills unit, even for credible increases in flux caused by a recurrence of pluvial climates.

### 3.1.3.2 Flow in the Saturated Zone

In the saturated zone, almost all flow beneath the repository site is probably through fractures. The parameters necessary for determining saturated flow velocities are expressed by

$$V_w = \frac{Ki}{n} \quad (3)$$

where  $V_w$  is the particle velocity for water,  $K$  is the hydraulic conductivity,  $i$  is the hydraulic gradient ( $\partial h/\partial \ell$ ), and  $n$  is the effective porosity of fractures; or from

$$V_w = \frac{F}{n} \quad (1)$$

where  $F$ , the flux, is equal to the hydraulic conductivity times the gradient.

The horizontal component of the hydraulic gradient in the central and east portions of the site is generally well established as about 0.00034 from observations of static-water levels in several drill holes throughout the Yucca Mountain area (J. H. Robison, USGS, personal communication) (Figure 6), though local variations from the regional gradient are likely. Preliminary

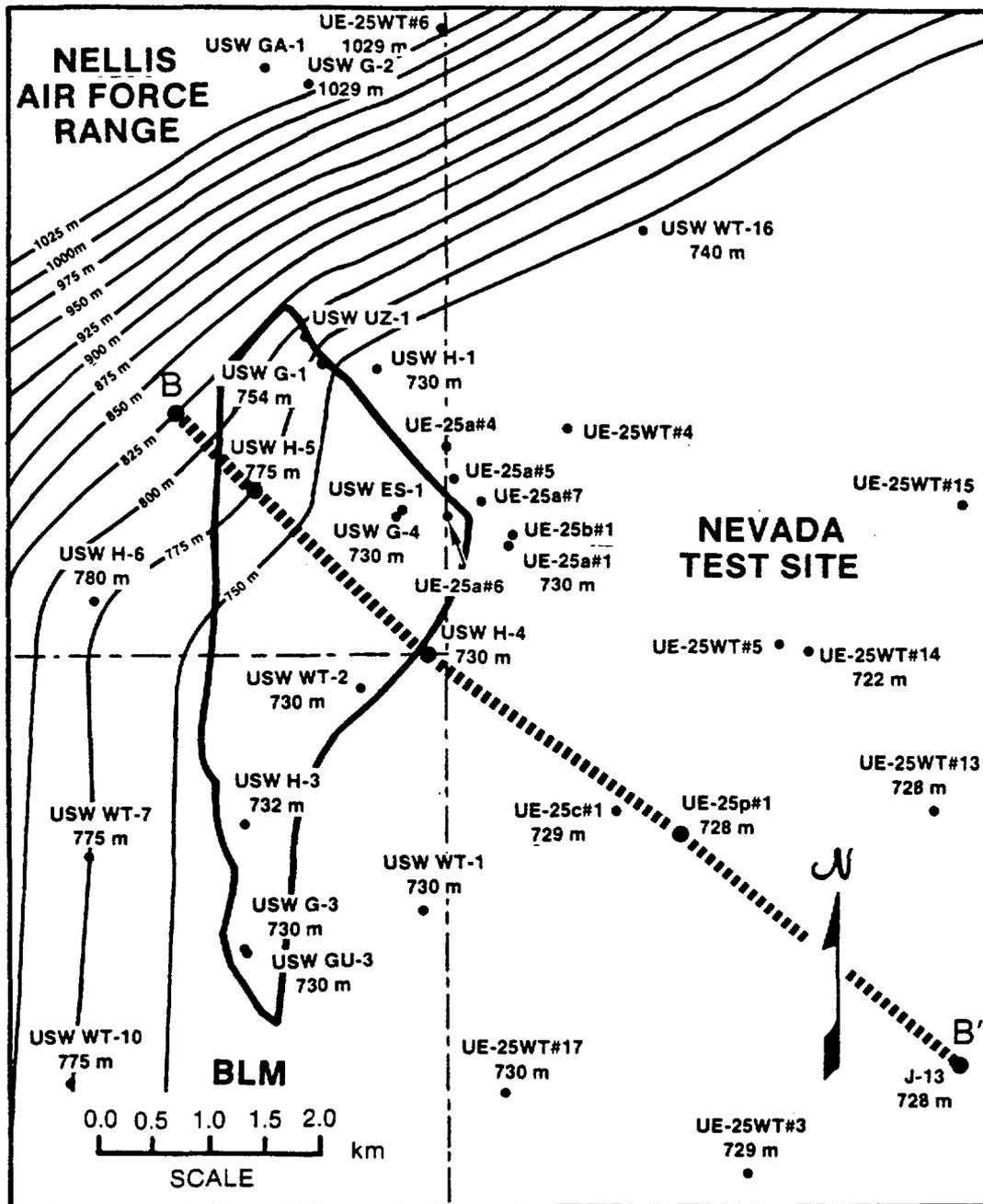


Figure 6. Water table contours and spot, static-water levels in drill holes at Yucca Mountain; B-B' shows the location of the hydrogeologic cross section in Figure 3.

data on head variations with depth indicate that the saturated volcanic rocks behave as an unconfined aquifer because head is nearly constant through the upper few hundred meters of aquifer thickness (J. H. Robison, USGS personal communication). Deeper in the volcanic section, head may increase, as indicated by measurements in drillhole USW H-1 (Rush et al., 1983). A carbonate aquifer occurs at a depth of about 1400 m in one drillhole, Ue25p#1, and exhibits higher head than the overlying, unconfined volcanic aquifer (J. H. Robison, USGS, personal communication). Thus, a confined aquifer may occur deep beneath the water table at Yucca Mountain, but recharge from the unsaturated zone should flow nearly horizontally at the water table along the gradient of the generally unconfined volcanic aquifer.

The effective porosity of fractures, though less well established than the gradient, probably falls within limits ranging from about 0.0005 to 0.005. These numbers are based on calculations of fracture apertures required to produce the rock-mass permeability for a given number of fractures per unit volume of rock (Table 3). This range is considerably less than the estimate by Thordarson (1983) of several percent for the effective porosity of the rock matrix of core samples and coincides at its upper end with the value estimated for fracture-flow systems in tuff by Blankenagel and Weir (1973).

The range of hydraulic conductivity for rocks along the saturated flow path is more difficult to determine. Carbon-14 ages of groundwater in the vicinity of Yucca Mountain (Figure 7) indicate that actual saturated-flow velocities are about 1 to 5 m/yr (Benson et al., 1983). These values yield saturated flow times of 2000 to 10,000 yr for 10 km. Assuming an effective porosity of 0.002 and a higher gradient of 0.001 to account for increasing water table levels north of Yucca Mountain, the groundwater ages suggest that the average effective conductivity is on the order of 25 m/yr.

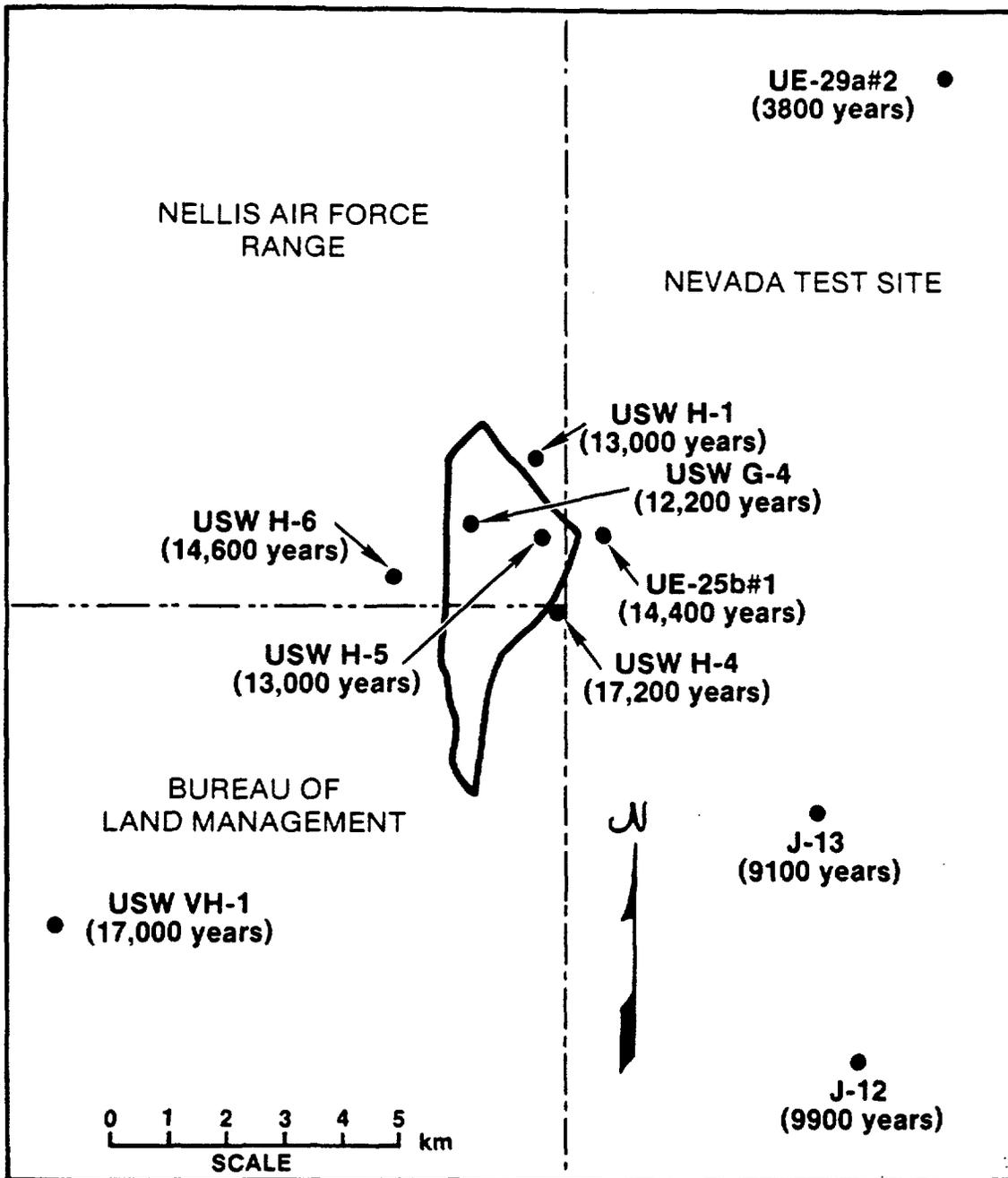


Figure 7. Groundwater ages determined by uncorrected C-14 dating of water samples from the saturated zone at selected drill holes in the vicinity of Yucca Mountain (from Benson et al., 1983).

A single aquifer test in well J-13 yielded an estimate of 1 m/d (365 m/yr) for the hydraulic conductivity of the Topopah Spring Member (Thordarson, 1983), which occupies about 30% to 40% of the flow path of concern (Figure 3). The rest of the saturated flow path is through the Calico Hills unit or older tuff. Hydraulic conductivities of these two units have been estimated from tests of nine packed-off test intervals in well J-13. The estimates range from 0.0057 to 0.15 m/d (about 2 to 50 m/yr) (Thordarson, 1983) with a logarithmic average of about 0.01 m/d (about 4 m/yr). Based on aquifer tests in well USW H-1, conductivities for the Calico Hills unit and older tuff range from about 0.0002 m/d (about 0.07 m/yr) to about 2 m/d (about 700 m/yr) (Rush et al., 1983; Barr, 1984). The lower values correspond to tests of either isolated depth intervals of several hundred meters occurring 600 m or more beneath the water table or of composite intervals 1000 m or more thick and excluding the upper few hundred meters of aquifer. The higher values from drillhole USW H-1 correspond to the upper 100 m or so of the saturated zone. The Topopah Spring Member is not saturated in USW H-1, so no conductivity estimates for it are available from the general area where waste would be emplaced.

The well tests show that high conductivity values of tens to hundreds of m/yr occur only at isolated depth intervals of single wells. These intervals are generally near the water table (Benson et al., 1983) and are probably characterized by unusually dense or open fractures. Several tests suggest that homogeneous conductivity is also limited horizontally to zones a few hundred meters in extent (Barr, 1984). In conjunction with data on groundwater ages, this information leads us to conclude that hydraulic conductivities of about 1 to 50 m/yr probably bound the range of effective values for flow paths greater than a few hundred to a thousand meters or so.

Another line of reasoning leads to much higher estimates of effective saturated conductivities. Because saturated flux through a unit area is equal to the hydraulic conductivity times the gradient, the values for conductivity assumed above, 1 to 50 m/yr, yield a unit flux of about  $1 \times 10^{-11}$  to  $5 \times 10^{-10}$   $\text{m}^3/\text{s}/\text{m}^2$  for a gradient of 0.00034. According to the flux estimates of about  $2 \times 10^{-6}$  and  $5 \times 10^{-7}$   $\text{m}^3/\text{s}$  per meter of aquifer width at point locations at Yucca Mountain (Waddell, 1982), the saturated flow regime would require more than 1000 to over 200,000 m of aquifer thickness, a ridiculous range, to transmit the total flux, given a conductivity of 1 to 50 m/yr. Because the regional gradient is known with relatively high confidence, the total flux calculated by Waddell (1982) would require conductivities on the order of several thousand meters per year, assuming a reasonable aquifer thickness of less than a few hundred meters.

Observations that most flow occurs in intervals less than 100 m thick, which commonly are dispersed only throughout the upper few hundred meters of the saturated zone (Benson et al., 1983), mean that either total aquifer flux is about 10 to 100 times less than estimated by Waddell (1982) or the hydraulic gradient times the hydraulic conductivity is 10 to 100 times greater than indicated by groundwater ages and aquifer tests. We believe that the lower conductivity estimates based on field data for groundwater ages and aquifer conductivities represent the situation at Yucca Mountain better than those inferred from regional flux estimates. This is because the regional estimates are based on large-scale modeling, which requires very broad assumptions and generalizations about hydrologic conditions. In contrast, the lower estimates of hydraulic conductivity are based on field data obtained at and near the Yucca Mountain site. However, even the lower estimates represent a significant capacity to transmit water.

Even for the low hydraulic gradient observed from drillholes throughout the Yucca Mountain area, saturated flow velocities are probably still high and saturated flow times to the accessible environment (at the end of 2- or 10-km flow paths) short as a result of high conductivities and low fracture porosities. If the high conductivities calculated from drill-stem tests and regional flux estimates are not continuous along individual flow paths, the total flux through the saturated zone may be less than currently estimated by Waddell (1982). In this case, average flow velocity might be dominated by slow flow through interspersed, less conductive portions of the flow path. This situation could occur if interconnected, high fracture conductivity is restricted laterally and vertically to isolated zones and the bulk of the gradient drop occurs in regions between these zones.

Though considerable uncertainty is associated with the hydraulic conductivity in the saturated zone, it does not contribute much to uncertainty about total flow time from a repository to the accessible environment if unsaturated flux is less than about 1 mm/yr. Such low flux through the unsaturated zone will yield flow times of tens of thousands of years, so the additional few hundred or thousands of years in the saturated zone would not significantly affect total flow time even if the accessible environment were to occur at the end of a 10-km saturated flow path.

In summary, the hydrologic environment at Yucca Mountain, particularly the unsaturated zone, offers a highly promising barrier for isolating wastes for very long times. However, under certain plausible, but unlikely, conditions of unsaturated flux greater than the maximum hydraulic conductivity of the matrix, currently believed to be about 1 mm/yr, groundwater flow from parts of the repository to the water table might be relatively rapid, though the total amount of water moving through the repository would remain small,

i.e., a few millimeters per year. Only under such unlikely conditions of flux would the saturated flow regime contribute significantly to total flow time to the accessible environment.

### 3.2 Geochemistry

The geochemical information needed for analysis of repository behavior is that which influences waste solubility and radionuclide transport. The geochemical conditions of primary concern for waste solubility are the Eh, pH, and dissolved solids of groundwater. These items are discussed in Section 3.2.1. Conditions that will influence radionuclide transport are discussed in Section 3.2.2; they determine how effectively the rocks will be able to retard radionuclide migration.

#### 3.2.1 Solubility

Though waste solubility will be affected by elevated temperatures caused by radioactive decay of the waste, it probably will be similar at the close of the containment period (300 to 1000 yr) to what it would be under current, ambient temperatures. This assumption is part of the broader general assumption given in Chapter 2, assumption 6. It is based on predictions of temperature histories for a repository in densely welded tuff (Peters, 1983; Johnstone et al., 1984; Klasi et al., 1982; Johnson, 1982; Sundberg and Eaton, 1982) that indicate temperatures less than 100°C will occur at the wall of emplacement holes before the end of the containment period, even if it lasts only 300 years. Because temperatures of less than 100°C are not expected to cause significant changes in the geochemical environment, we tentatively conclude that decay heat from the waste will not significantly affect waste solubility. Accordingly, our analyses of waste dissolution are based on

information about geochemical conditions that currently exist in the host rock.

No data are available on the chemistry of water from the target emplacement horizon because of the difficulty of obtaining water samples from the unsaturated zone. However, chemical analyses of water samples from tuffaceous aquifers in and around the site have been made (Benson et al., 1983). Assuming that water in these aquifers reached its present chemical condition, at least in part, because it passed through rocks in or similar to those in the unsaturated zone at the site, the dissolved solids in the unsaturated zone should be similar to those in the saturated zone. Extrapolating the pH and, particularly, the Eh of the water from the saturated zone to the unsaturated zone is more difficult to justify. Therefore, the following discussion of water chemistry at Yucca Mountain should be interpreted cautiously in light of the uncertainties associated with the correspondence between unsaturated and saturated conditions.

Generally, the water at Yucca Mountain is benign in terms of its inherent capability to dissolve nuclear waste in either glass or spent fuel forms (Kerrisk, 1984). The content of dissolved solids is generally a few hundred parts per million, predominantly sodium cations and bicarbonate anions (Table 4). The pH is nearly neutral (pH = 7) to slightly alkaline (pH < 8 or so) (Benson et al., 1983). Estimates of the Eh suggest that oxidizing conditions up to about 700 mV may occur. These estimates are based on an assumption that free oxygen is available from the atmospheric gases in the unsaturated zone and that the liquid water is saturated with oxygen.

Under these conditions the water at Yucca Mountain is geochemically suitable as an excellent source of drinking water. Its potential reactivity with emplaced waste would, by analogy, be similar to the corrosion occurring

Table 4. Chemical composition of water samples from selected drill holes in the vicinity of Yucca Mountain (from Benson et al., 1983).

Borehole	Onsite pH (units)	Laboratory pH (units)	Water temperature (°C)	Dissolved constituents (mg/l)											
				Ca	Mg	Na	K	HCO <sub>3</sub> field	HCO <sub>3</sub> laboratory	Cl	SO <sub>4</sub>	SiO <sub>2</sub>	Li	Sr	F
UE-25b#1	7.1	6.8	36.0	19	0.73	53	3.7	173	158	13	24	53	0.950	0.044	1.5
UE-25b#1	7.5	7.5	36.0	17	0.59	46	3.5	139	134	8.5	22	52	0.220	0.038	1.6
UE-25b#1	7.1	7.7	37.2	18	0.72	46	2.8	133	138	7.5	21	51	0.120	0.047	1.6
UE-29a#2	7.2	7.6	25.1	10	0.2	44	1.1	107	112	11	22	44	0.100	0.039	1.0
UE-29a#2	7.0	7.4	22.7	10	0.3	44	1.3	107	110	8.8	21	44	0.110	0.033	.9
USW H-1	7.7	7.8	33.0	4.5	<0.1	51	2.4	---	115	5.7	18	47	0.040	0.005	1.2
USW G-4	7.7	7.5	35.6	13	0.2	57	2.1	139	143	5.9	19	45	0.067	0.017	2.5
USW H-1	7.5	8.0	34.7	6.2	<0.1	51	1.6	---	122	5.8	19	40	0.040	0.020	1.0
USW H-4	7.4	7.9	34.8	17	0.29	73	2.6	173	171	6.9	26	46	0.130	0.027	4.6
USW H-5	7.8	7.8	36.5	1.9	0.01	60	2.1	126	124	6.1	16	48	0.062	0.009	1.4
USW H-5	7.9	8.0	35.3	2.0	<0.01	60	2.1	127	124	6.1	16	48	0.071	0.004	1.4
USW H-6	8.1	8.3	37.8	4.1	0.09	86	1.3	182	188	7.6	29	48	0.082	0.008	4.7
USW VH-1	7.9	8.0	35.2	11	1.6	79	1.9	167	158	11	44	50	0.090	0.070	2.7
USW VH-1	7.5	7.9	35.5	10	1.5	80	1.9	165	158	10	45	50	0.090	0.070	2.7
USW VH-1	7.5	8.0	35.5	9.9	1.5	78	1.8	162	158	10	44	49	0.090	0.060	2.7
J-12	7.1	---	27.0	14	2.1	38	5.1	---	119	7.3	22	54	0.040	0.010	2.1
J-13	7.2	---	31.0	12	2.1	42	5.0	---	124	7.1	17	57	0.040	0.020	2.4

when a drinking glass is filled with aerated water from a typical kitchen faucet. During the long time desired for containment of the wastes in a repository, such rates would, of course, slowly dissolve some of the waste; the analogy is made only to point out that water at Yucca Mountain is not, in any sense, an unusually corrosive agent.

The solubility of uranium has been calculated by two geochemical models of equilibrium reactions using as a basis for computation the chemical characteristics of water from the saturated zone near the site (see data for Well J-13, Table 4) and on assumed oxidation and pH states (Figure 8). Wolfsberg and others (1982) and Daniels and others (1982) used the EQ3 model (Wolery, 1979) to estimate uranium solubilities alone and in the presence of plutonium. Because plutonium tends to tie up most available carbonate as  $\text{PuCO}_3^{2+}$ , less uranium carbonate gets into solution than when plutonium is not present. As a result, uranium solubility for a pH of 6.9 and an Eh range of 700 to -200 mV was calculated to range from about  $3.4 \times 10^{-6}$  to  $1.6 \times 10^{-11}$  mol/l in the presence of plutonium and from about  $3.0 \times 10^{-4}$  to  $1.5 \times 10^{-11}$  mol/l if plutonium is absent. As the Eh increases, or if the equilibrium constant of  $\text{PuCO}_3^{2+}$  is low (freeing carbonate in solution), the solubility of uranium increases (Figure 8). Using another geochemical model, MINTEQ (Felmy et al., 1984), Thompson and others (1984) calculated uranium solubilities of about  $10^{-6}$  to  $5 \times 10^{-11}$  mol/l for Eh values ranging from 788 to -400 mV, respectively, and a pH of 7.5 (Figure 8). These calculations indicate that under the probable pH and Eh conditions of the host rock at Yucca Mountain, the solubility of uranium in spent fuel would be less than about  $10^{-4}$  mol/l and perhaps as low as  $10^{-6}$  or  $10^{-7}$  mol/l.

From assumption 5, Chapter 2, the annual dissolution rate of uranium,  $DR_u$ , will be

$$DR_u = S_u \cdot Q \quad (5)$$

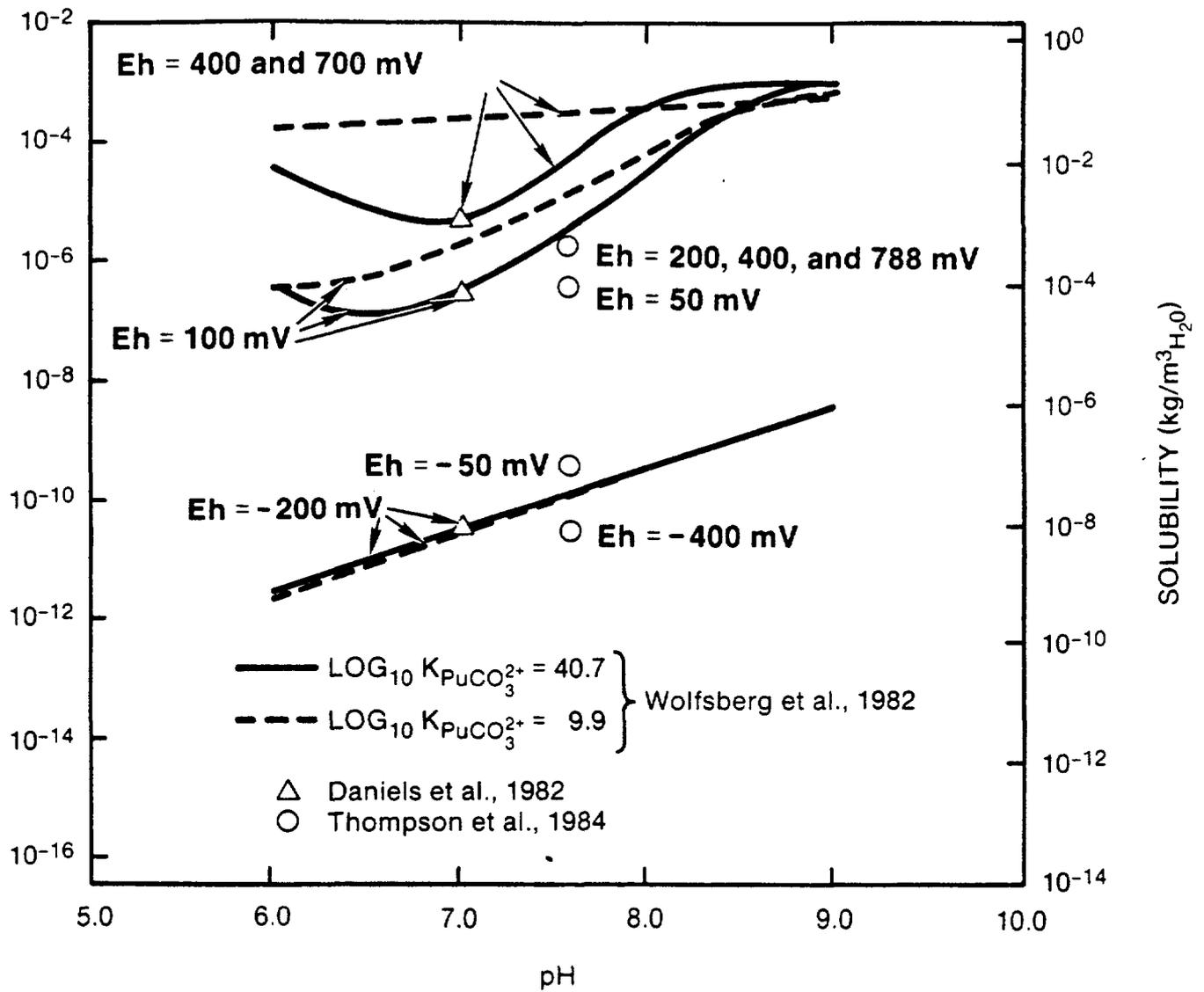


Figure 8. Solubilities of uranium calculated for various Eh and pH conditions in water with a composition similar to that from Yucca Mountain (J-13 water, see Table 4); (from Wolfsberg et al., 1982; Daniels et al., 1982; and Thompson et al., 1984).

where  $S_u$  is the solubility limit of uranium expressed in kg/m<sup>3</sup> of water (mol/l x 0.238 kg/mol x 1000 l/m<sup>3</sup>) and  $Q$  is the annual water flux in cubic meters interacting with the waste. For other waste species,  $i$ , the annual dissolution rate,  $DR_i$ , is then

$$DR_i = DR_u [M_i/M_u] \quad (6)$$

where  $M_u$  and  $M_i$  are, respectively, the mass of uranium and the mass of species  $i$  in the spent fuel. An implicit assumption in this equation is that the release of all radionuclides from the repository will be limited by the solubility of uranium. This assumption is probably conservative because some waste species have lower solubilities than uranium (Kerrisk, 1984). For species with higher solubilities than uranium, including cesium and technetium, both the kinetic limitations on dissolution rates in flowing water and the generally homogeneous distribution of many of these species in the spent-fuel matrix are likely to slow effective dissolution rates to values more nearly congruent with uranium (Kerrisk, 1984; Braithwaite, 1984). Some species with higher solubilities than uranium may be somewhat segregated in the spent fuel, including carbon in the zircalloy cladding, iodine in the gaps between the fuel and cladding, and cesium in the fuel itself.

The oxidizing nature of the groundwater is a potentially adverse condition at Yucca Mountain that requires special attention. However, the low flux of water, in combination with potentially reducing environments provided by steel and zircalloy in the engineered barriers, will, in all likelihood, adequately compensate for the ambient oxidizing environment.

### 3.2.2 Radionuclide Retardation

In terms of potential effects on radionuclide transport, the geochemical environment is, perhaps, one of the most favorable aspects of the Yucca Mountain site. Assuming that groundwater flow, in conjunction with hydrodynamic dispersion, sets an upper limit on the velocity for dissolved radionuclides to move away from a repository, geochemical and related physical interactions among the wastes, groundwater, and surrounding rocks can only enhance site performance by slowing radionuclide movement. Processes such as mineral precipitation, ion exchange, absorption, and adsorption will slow the movement of radionuclides relative to groundwater flow. The characteristics of the rocks at Yucca Mountain are highly conducive to all these retardation processes. Though the differences among these processes are recognized, their combined effects on radionuclide movement are commonly referred to in this report as retardation, recognizing that the term sorption is generally reserved for a specific subset of reactions.

As mentioned in Chapter 2, assumption 10, the velocity of radionuclide movement relative to groundwater movement through the rock matrix is obtained by a retardation factor,  $R_d$ . For a particular radionuclide,  $i$ , assuming equilibrium conditions:

$$R_{d_i} = K_{d_i} (\gamma/n) + 1 \quad (7)$$

where  $\gamma$  is the bulk density of the rock and  $n$  is the effective porosity, and  $K_d$  is the sorption ration, which depends on the rock and the radionuclide. The average velocity for a particular radionuclide,  $V_i$ , is then

$$V_i = V_w / R_d \quad (8)$$

where  $V_w$  is the average particle velocity of water.

The relatively high porosity of the tuff units (Table 3), combined with the generally small size of the pores, offers a large surface area for geochemical and physical interactions between the rock and moving radionuclides. At least in part because of this structural fabric, sorption of radionuclides by the tuffs at Yucca Mountain, independent of mineralogical composition, will in all likelihood be very high. Values for the sorption ratio,  $K_d$  (expressed in ml/g), are generally more than 100 for cationic waste species, including cesium, strontium, plutonium, americium, barium, and tin (Table 5). For anionic species, such as technetium, iodine, and carbon, sorption ratios are generally low, i.e., less than 1, and may be zero (Table 5). Some radionuclides, including uranium and neptunium, are retarded by sorption values greater than 1 but less than 10 (Table 5).

For densely welded tuff with a density of about 2 g/ml and an effective matrix porosity of about 10%, radionuclide velocity will be on the order of 0.05 times the groundwater velocity for a  $K_d$  of 1. For a  $K_d$  of 100, the radionuclides will move about  $5 \times 10^{-4}$  times the velocity of water. For nonwelded tuff, radionuclide velocities will be about 0.2 and 0.002 times the velocity of water for  $K_d$ 's of 1 and 100, respectively, assuming a density of 1.5 and a porosity of 30%.

Thick zones composed predominantly of zeolite minerals occur below the potential emplacement horizon in portions of the Calico Hills unit and the older tuff. Zeolites have abundant cations available for exchange plus a peculiar, open, crystal-lattice structure that allows access for waste species to regions deep within the lattice. Partly because of these peculiarities, zeolites have a greater capacity for sorption than many other minerals. Several waste elements have  $K_d$ 's of more than 1000 in the Calico Hills unit (Table 5), so the rocks below the emplacement horizon may slow the velocity of

Table 5. Representative sorption ratios, Kd's, of selected radionuclides in the matrix materials of different rock units at Yucca Mountain (from Daniels et al., 1982; 1983).

Tuff unit	Waste element	Sorption ratio, Kd (mL/g)
Topopah Spring Member (welded tuff)	Americium (Am)	1,200
	Cesium (Cs)	290
	Neptunium (Np)	7
	Plutonium (Pu)	64
	Strontium (Sr)	53
	Technetium (Tc)	0.3
	Uranium (U)	1.8
	Barium (Ba)	900
Topopah Spring Member (bedded tuff)	Americium (Am)	180
	Cesium (Cs)	16,000
	Neptunium (Np)	NA
	Plutonium (Pu)	120
	Strontium (Sr)	17,000
	Technetium (Tc)	2.5
	Uranium (U)	2.5
	Barium (Ba)	38,000
Tuffaceous Beds of Calico Hills (bedded tuff)	Americium (Am)	4,600
	Cesium (Cs)	7,800
	Neptunium (Np)	11
	Plutonium (Pu)	140
	Strontium (Sr)	3,900
	Technetium (Tc)	NA
	Uranium (U)	5.3
	Barium (Ba)	94,000
Prow Pass Member (partially welded tuff)	Americium (Am)	470
	Cesium (Cs)	190
	Neptunium (Np)	6.4
	Plutonium (Pu)	77
	Strontium (Sr)	22
	Technetium (Tc)	0.2
	Uranium (U)	NA
	Barium (Ba)	182
Bullfrog Member (welded tuff)	Americium (Am)	140
	Cesium (Cs)	180
	Neptunium (Np)	NA
	Plutonium (Pu)	80
	Strontium (Sr)	62
	Technetium (Tc)	4.2
	Uranium (U)	1.3
	Barium (Ba)	400
Tram Member (nonwelded tuff)	Americium (Am)	28,000
	Cesium (Cs)	610
	Neptunium (Np)	28
	Plutonium (Pu)	400
	Strontium (Sr)	290
	Technetium (Tc)	NA
	Uranium (U)	4.6
	Barium (Ba)	760

NA = no data available.

cationic waste species moving with matrix-water flow by a factor of 20,000 or more relative to groundwater flow velocity.

For flow through fractures, less rock is in direct contact with moving water; hence, direct retardation by sorption is less effective than for flow through the matrix. A retardation factor for sorption in fracture flow is given by Burkholder (1976) whereby

$$Rd_i = 1 + AKa_i \quad (9)$$

where A is the ratio of surface area to void volume along fractures through which flow occurs, and Ka is an expression of Kd in terms of ml/cm<sup>2</sup> of reactive surface area. Assuming that fracture surfaces are smooth (i.e., have no roughness coefficient), A, conservatively, is equal to 2 divided by the width of the fracture, and the retardation factor for species i becomes

$$Rd_i = 1 + (2Ka_i / b) \quad (10)$$

where b is the fracture aperture width (Freeze and Cherry, 1979). This results in much less effective sorption for a given radionuclide in fracture flow than in matrix flow. For example, minerals along fracture surfaces would need Kd's of about 500 to retard radionuclide movement by a factor of only 2, assuming that Kd's from laboratory tests were calculated on the basis of 1 g of sorbing minerals possessing about 50 m<sup>2</sup> of surface area (Daniels et al., 1982) and that fracture apertures are about 10 μm wide (Table 3). Similarly, Kd's of 5000 and 50,000 would retard radionuclide movement in fractures by factors of about 10 and 100, respectively. If the apertures are narrower or wider, the retardation by direct sorption along the fractures would proportionally increase or decrease, respectively.

Effective retardation along fractures is likely to be much greater than actual retardation provided by sorption alone. The potential for diffusion of waste species along a concentration gradient into the rock matrix from solutions moving through fractures may significantly delay radionuclide movement (Neretnicks, 1980; Neretnicks et al., 1982; Rasmuson and Neretnicks, 1981; Walter, 1982; Grisak and Pickens, 1980). The generally high porosity of the tuffs at Yucca Mountain provides a large reservoir of storage space for waste species moving through fractures, even if the contaminated water in the fractures does not itself move into the rock matrix. Rather than a true retardation of radionuclide movement relative to fluid flow, this process will cause a transfer of waste mass from fluid in the fractures to fluid in the matrix. It will continue until the storage space in the matrix, determined by sorption equilibrium concentrations, is filled. Once in the matrix, the waste species will move with the porous water flow, subject to retardation by sorption. In effect, the radionuclides initially in the fractures are thereby "retarded" relative to fracture flow and fracture sorption.

In the tuffs at Yucca Mountain, this diffusion process will in all likelihood significantly compensate for rapid water flow and less effective sorption within fracture-flow systems. Diffusion will occur in the unsaturated zone under the unlikely case that the water flux exceeds the carrying capacity of the rock matrix and fracture flow occurs. Diffusion will also contribute to retardation in the saturated zone, where fracture flow is dominant under prevailing conditions. In the unsaturated zone, chemical diffusion due to concentration differences will be strongly accentuated by water advection along a hydraulic gradient as discussed in Section 3.1.3.1. The process also will significantly retard anionic or nonsorbing cationic species such as

carbon, technetium, and iodine, thus strongly compensating for the lack of sorption of these species.

Diffusion into the rock matrix has been quantified for some rocks along the flow paths at Yucca Mountain (Travis et al., 1984). That study substantiates the conclusion that diffusion is potentially a significant mechanism for retarding the net movement of radionuclides relative to water-flow velocities in fractures. Travis and others show that diffusion may provide delay factors of several hundred for nonsorbing species and several thousand for sorbing species. In summary, ample evidence indicates that the geochemical conditions at Yucca Mountain will strongly inhibit the movement of radionuclides toward the accessible environment by both sorption and diffusion.

### 3.3 Rock Characteristics

The rock properties relevant for assessing repository behavior generally are related to the changes caused by repository development in the ability of the rock to transmit water toward and away from waste and the changes in water chemistry that might affect waste solubility. For the purposes of this report, these properties are restricted to the thermal and mechanical properties of the rock matrix and exclude existing structures such as fractures, faults, and stratigraphic features. These latter types of rock-mass features are addressed under geohydrology (Section 3.1) in the context of their effect on groundwater movement and its prediction. For this discussion the rock characteristics of primary concern are thermal conductivity, thermal expansion, and rock strength.

The vertical and lateral extent of rocks with properties amenable to accommodating the effects of repository construction and heat from the waste

is another concern for rock characteristics. The variability of rock properties within a rock mass is an issue for siting only insofar as the range in properties exceeds some threshold of acceptability in terms of specific performance requirements. The greater the spatial extent of a rock mass with a set of properties within these thresholds, the greater will be the flexibility for relocating waste emplacement areas during design or construction should it become necessary to avoid some local, undesirable rock conditions. Mansure and Ortiz (1984) addressed this concern and concluded that considerable flexibility in the placement of waste is provided by the lateral extent of the host rock. We assume that emplacement will occur within the area outlined in Figure 1. Alternative options for the location of waste emplacement are not considered in this report, though there is no currently known reason to restrict waste emplacement to that area. It is further assumed that the thermal and mechanical properties of the host rock are relatively uniform throughout the emplacement area.

Current knowledge of the thermal and mechanical properties of the densely welded Topopah Spring Member indicate that the host rock will adjust to repository-induced perturbations without causing significant changes in isolation capabilities. The thermal conductivity of the host rock is about  $2 \text{ W/m}\cdot\text{C}$  (Johnstone et al., 1984). This is sufficient to transmit heat from the waste rapidly enough to keep rock temperatures below  $100\text{C}$  a few meters to a few tens of meters away from the waste canisters for emplacement densities up to about  $25 \text{ thermal W/m}^2$  ( $100 \text{ kW/acre}$ ) (Figure 9B) (Johnstone et al., 1984; Peters, 1983; Klasi et al., 1982; Johnson, 1982; Sundberg and Eaton, 1982). The actual emplacement density is expected to be much lower than  $25 \text{ W/m}^2$  as indicated in assumption 3, Chapter 2 and evaluated for Figure 9A. Thus, in support of the assumption discussed in Section 3.2, the effects of repository

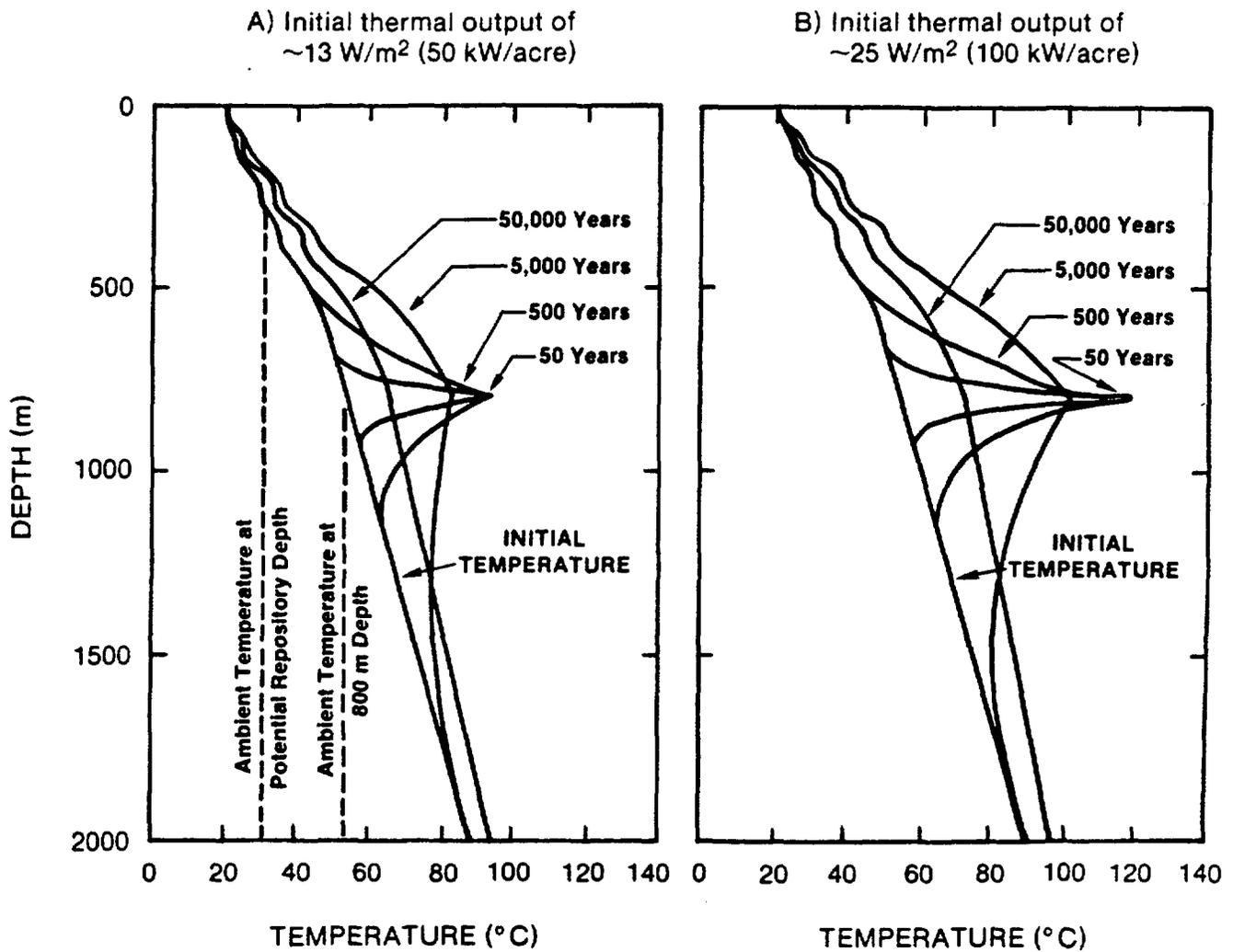


Figure 9. Vertical temperature profiles for a repository 800 m deep in densely welded tuff of the Bullfrog Member (see Table 2); ambient temperature at the current reference depth of about 350 m in the Topopah Spring Member is about 20 degrees C less than at depths assumed for the calculations (see Part A), so temperatures above and below a repository at 350 m would be about 20 degrees less than shown by the profiles (modified from Klasi et al., 1982).

heat on waste solubility, even at unrealistically high emplacement densities, are not expected to be significant after the containment period.

In the context of the natural stress environment at Yucca Mountain and the shear strength of densely welded tuff, additional stresses caused by thermal expansion should cause little or no new fracturing of the rock mass surrounding a repository. Shear movement along existing fractures should be limited to rocks within a few meters of the emplacement drifts (RE/SPEC, 1982; Johnstone et al., 1984).

Zeolite minerals, which occur in abundance in portions of the Calico Hills unit 50 m or more beneath the potential emplacement horizon, tend to dehydrate with increasing temperature. Temperatures in the highly zeolitic rocks are expected to peak at about 85°C 1000 yr after repository closure, thus always remaining below temperatures that would induce significant shrinkage of minerals and attendant changes in fracture apertures (Figure 10) (Johnstone et al., 1984; Klasi et al., 1982; Smyth, 1982). As a result, little or no change is expected in the hydrologic properties of the host rock or surrounding units due to fracturing from either construction of a repository or heat generated by radioactive decay of the waste.

Even if fracturing caused by heat were to occur, the changes probably would have negligible effects on water movement through the already fractured rocks in the unsaturated zone. This follows from the discussion in Section 3.1.3, where it was shown that the amount of water moving through fractures depends on the relation between the matrix hydraulic conductivity and total water flux. Neither the hydraulic conductivity, density, nor the location of fractures will greatly influence the partitioning of water flow between the rock matrix and the fractures; therefore, neither the amount nor the velocity of water reaching or leaving the repository should be noticeably affected by

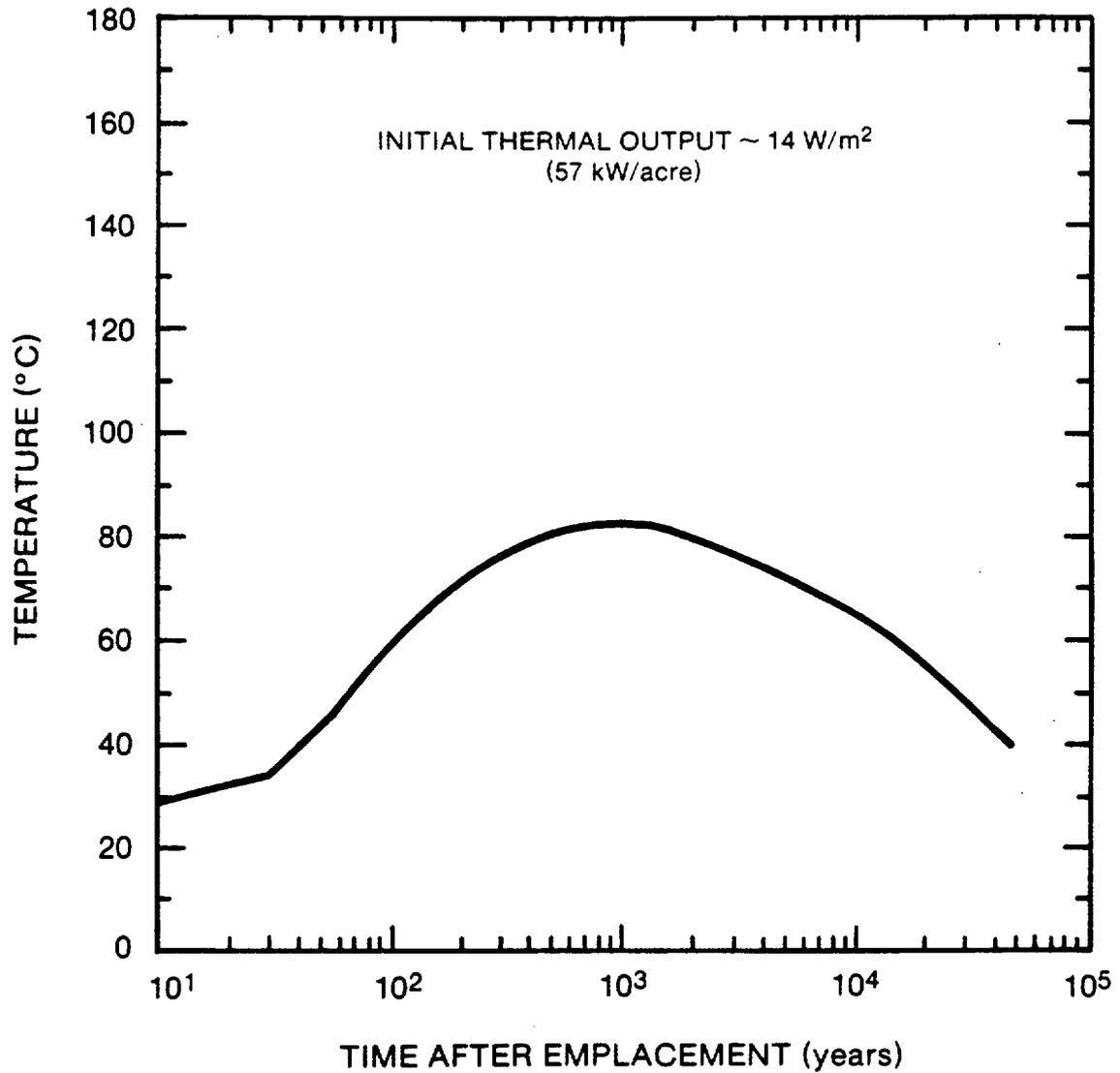


Figure 10. Temperature projections 50 m below a repository in the densely welded Topopah Spring Member (from Johnstone et al., 1984).

creation of new fractures or the opening or closing of existing fractures. For the portion of flux, if any, moving through fractures, flow velocities probably will be rapid because of low fracture porosity. Any changes in fracture apertures or density would tend to change effective fracture porosity. Depending on the number and size of fractures transmitting the water before the changes, such changes may or may not affect the velocity of water movement. Such changes, in any event, would occur only within a few tens of meters, at most, around the wastes and would have negligible effects on total flow time between the repository and the accessible environment.

The potential liberation of water under heating of mineral, especially zeolites that make up some of the tuffs of Yucca Mountain, may increase the volume of freely moving liquid water in rocks several meters from the waste. However, zeolites only occur tens of meters below the repository horizon where temperature increases and the associated amounts of liberated water are expected to be small. Near the waste, pore water would tend to be driven outward from the waste during the period of increasing temperatures (Pruess and Wang, 1983). During cooling, this water may migrate back toward the waste, eventually reestablishing the level of saturation that existed before waste emplacement. Thus, by the close of the containment period (300 to 1000 yr), the geochemical and hydrologic environments are expected to be similar to those now occurring. As a result, we do not explicitly account for potential changes in ambient conditions induced by repository activities for analyses of performance described in the following chapter.

## CHAPTER 4. PERFORMANCE IN RELATION TO REGULATORY REQUIREMENTS

This chapter describes results of calculations of groundwater flow times, waste-dissolution rates, and releases of radionuclides at the accessible environment under a range of conditions for groundwater flux past the wastes in a repository at Yucca Mountain. The chapter is organized to address the distinct performance objectives of the NRC and the EPA. Groundwater flow time is addressed in Section 4.1 and compared to the NRC 1000-yr requirement. Section 4.2 addresses the ability of the site to comply with the NRC requirement for an annual release rate from the repository of less than 1 part in 100,000 of the curie content of individual radionuclides. Section 4.3 uses the release rates presented in Section 4.2 as a source term for calculations of radionuclide transport to the accessible environment by water movement as established in Section 4.1. Most transport calculations use only sorption as a geochemical-retardation mechanism. The results of transport calculations are discussed in terms of the EPA release limits.

All calculations were done by a computer program developed by J. P. Brannen and Y. T. Lin. The program has not been verified formally, but spot comparisons of its output with the results of manually performed analytical exercises have been made and show agreement. Description of the theoretical basis for the calculations is presented in Appendix A. The program is listed in Appendix B.

### 4.1 Groundwater Flow Time

Analyses in this section address the NRC performance objective for the natural site; that is, the requirement for a prewaste emplacement,

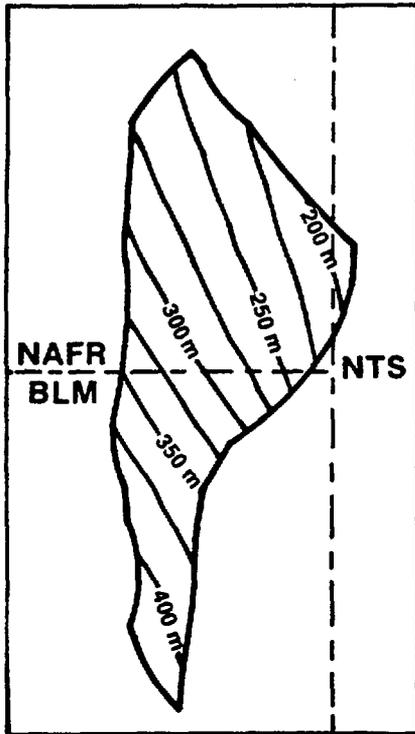
groundwater-travel time of 1000 yr from the disturbed zone around a repository to the accessible environment (NRC, 1983). Results from these analyses may also be interpreted to assess whether Yucca Mountain possesses the disqualifying condition for geohydrology listed in the DOE siting guidelines (DOE, 1983).

At this time, the boundaries of neither the disturbed zone nor the accessible environment are clearly defined. We assume that the disturbed zone extends downward from the repository no farther than the base of the densely welded portion of the Topopah Spring Member (including the vitrophere which occurs near its base). The thickness beneath the repository of the disturbed zone defined in this manner is shown in Figure 11B and varies from more than 100 m in the east to just under 50 m in the west. As discussed in Section 3.3, temperatures at the edge of the disturbed zone where it has a minimum thickness of 50 m will reach a maximum of about 85°C about 1000 yr after emplacement of the waste. This compares to an ambient temperature of about 30° to 40°C at the base of the Topopah Spring Member. The NRC defines the disturbed zone as the region around a repository where changes caused by repository development would significantly affect radionuclide transport (NRC, 1983). Because no mechanisms have been identified that suggest how an increase in temperature from about 40° to 85°C or less would significantly alter the transport of radionuclides, particularly in the unsaturated zone, this definition of the disturbed-zone boundary provides a conservative basis for calculating groundwater travel times.

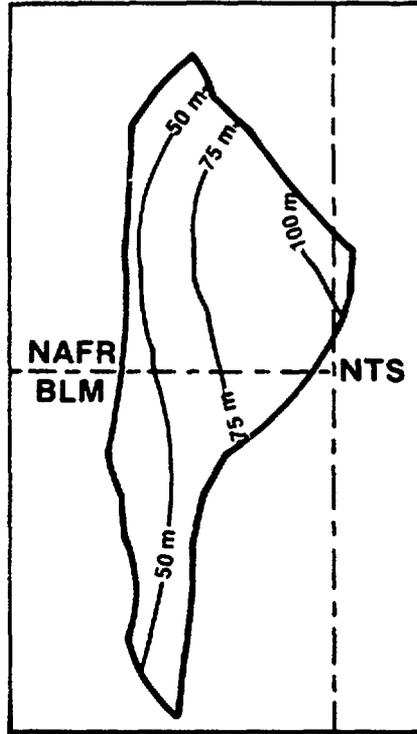
We assume three cases for the definition of the accessible environment. All are based on definitions proposed by the EPA. The first case (Case A) is based on an unpublished working draft of 40 CFR 191 (EPA, 1984), which can be interpreted to require the accessible environment to include the saturated

aquifer immediately beneath the repository. Though we believe this is an unnecessarily restrictive definition, considering the historical land-use control at the Nevada Test Site and more economical access to water supplies from the same aquifer in the basins immediately surrounding Yucca Mountain, we use it as a conservative case. The flow path of concern for this case is composed of only the vertical, unsaturated flow from the base of the densely welded tuff to the water table, i.e., flow through the unsaturated Calico Hills unit (Figure 3). In detail, the actual path to the aquifer underlying the host rock may include some vertical or inclined flow through some undetermined thickness of poorly transmissive rocks just below the water table or some inclined, tortuous, or locally lateral flow in the unsaturated zone. For simplicity, however, we conservatively assume for Case A that the water table (actually, the composite potentiometric surface observed as static water levels in wells) constitutes the accessible environment and coincides with the top of a horizontally flowing, unconfined aquifer in the saturated portion of the Calico Hills and older tuff units. The thickness of the unsaturated zone beneath the disturbed zone, as defined, varies throughout the Yucca Mountain site and generally exceeds 100 m (Figure 11, Part C). We assume the flow path of concern for Case A is composed of 100 m of the unsaturated Calico Hills unit. This is a conservative assumption because the 100-m thickness of unsaturated Calico Hills unit occurs where the thickest section, more than 100 m, of unsaturated Topopah Spring unit underlies the potential repository (Figure 11).

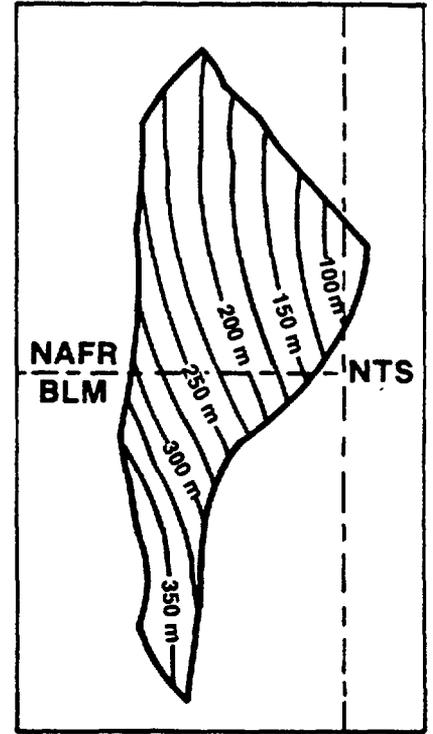
The second case for defining the accessible environment (Case B) is based also on the working draft of 40 CFR 191 (EPA, 1984). For this case the boundary of the accessible environment is assumed to occur 2 km in a horizontal direction from the waste-emplacement area. For our analyses we interpret this



A) Repository to water table



B) Topopah Spring Unit below repository



C) Calico Hills Unit below repository

Figure 11. Contours of the thickness of unsaturated rock beneath the proposed repository area; Parts B and C represent component thicknesses of the total thickness shown in Part A (from IGIS, 1984).

to mean that the accessible environment occurs in the saturated zone at the end of a 2-km flow path. The flow path of concern for this case is composed of vertical flow to the water table, described for Case A, plus 2 km of horizontal flow in the saturated zone (Figure 3). Assuming that the 2 km of horizontal distance corresponds to 2 km of flow path means that we take no credit for tortuous saturated flow.

The third case (Case C) is based on the published, proposed version of 40 CFR 191 (EPA, 1982). This case assumes the accessible environment is located 10 km horizontally from the waste emplacement area. We treat the distinction between Cases B and C by assigning a 200-yr flow time in the saturated zone to Case B and a 2000-yr flow time to Case C. Though the different flow times in the saturated zone for Cases B and C are generally intended to address alternative definitions of the accessible environment, they also may be interpreted to encompass uncertainty in flow time for a path of fixed length caused by uncertainty about hydraulic conductivity and effective porosity.

Results of groundwater travel-time calculations for all three cases and for the most likely flux of less than 1 mm/yr through the unsaturated zone are shown in Figure 12. Calculations of flow time solely through the unsaturated zone (Figure 12, Case A) are based on Equation 1 in Section 3.1.3. An effective porosity of 0.2 was used to provide a conservative basis for flow velocity through the matrix material of the zeolitic Calico Hills unit. Flow time is obtained simply by dividing the velocity by the flow distance of 100 m. As pointed out in Section 3.1.2, flux through the unsaturated zone probably is limited to a value equal to the hydraulic conductivity under observed moisture tensions of more than 20,000 cm. We assume the unsaturated conductivity is equal to the flux because the gradient is 1. Therefore, values for flux used

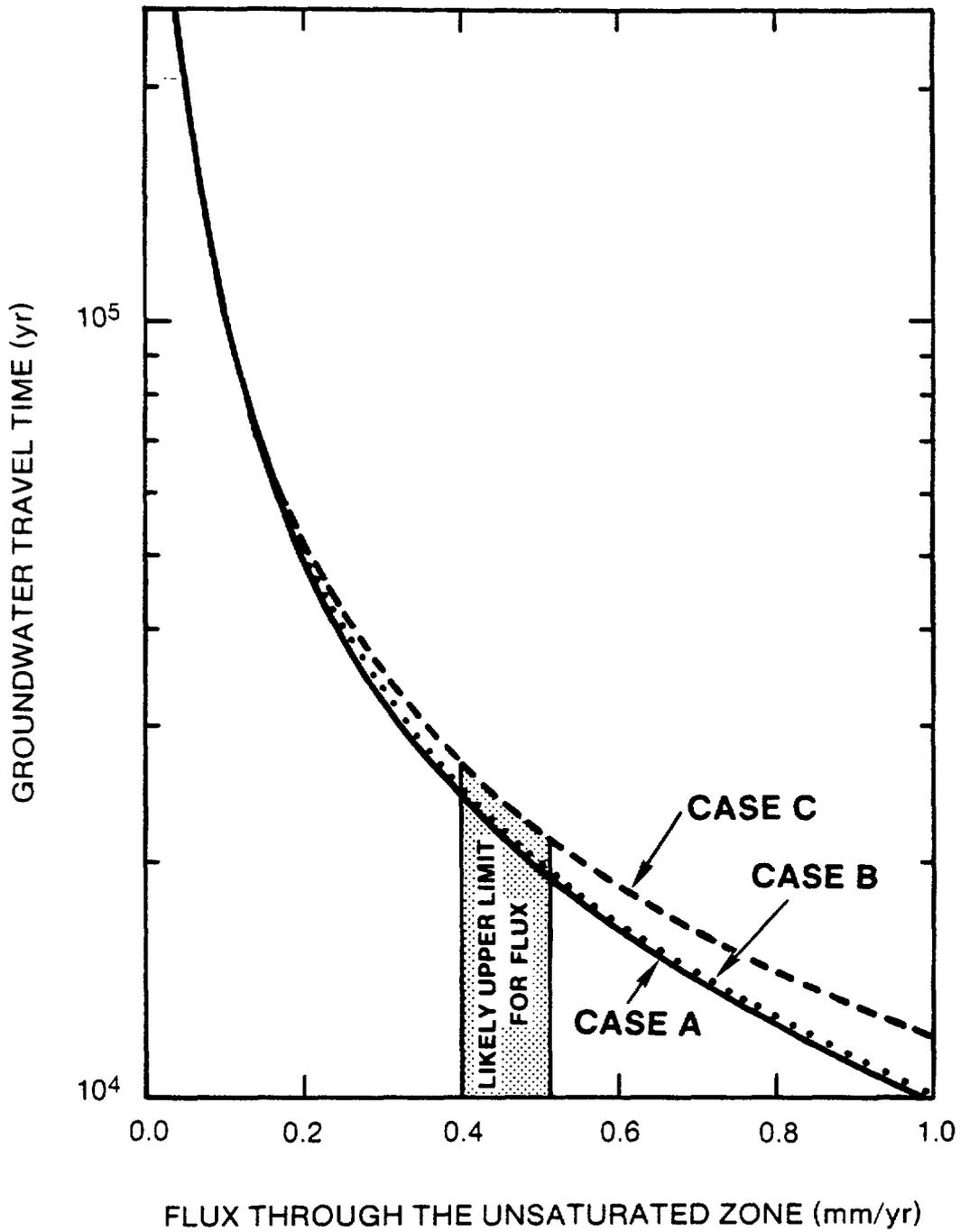


Figure 12. Fastest groundwater flow times from the disturbed zone to the water table (Case A), to the end of a 200-yr saturated flow path (Case B), and to the end of a 2000-yr saturated flow path (Case C); all cases based on a likely flux through the unsaturated zone of less than 1 mm/yr.

for the unsaturated part of the flow path (Figure 12, Case A) may be conservative for values greater than a few tenths of a millimeter per year. If the flux, as expected (see Section 3.1.2), is less than 0.5 mm/yr, unsaturated-flow time will exceed 20,000 yr; it will exceed hundreds of thousands of years if the flux is less than about 0.1 mm/yr (Figure 12). Under expected conditions, then, flow time is well in excess of the 1000-yr requirement, even if the accessible environment occurs at the water table immediately beneath the repository (Figure 12, Case A).

For all conditions of flux through the unsaturated zone, flow time in the saturated zone is assumed to be a constant of either 200 yr (Case B) or 2000 yr (Case C). Flow time in the saturated zone,  $T_s$ , was determined by considering the site properties expressed by the equation:

$$T_s = D \left( \frac{Ki}{n} \right)^{-1} \quad (11)$$

where D is a flow distance of 10 km; K is the saturated hydraulic conductivity of either 30 or 300 m/yr and represents alternative bulk-rock-mass conductivities; i is the hydraulic gradient of 0.00034; and n is an effective fracture porosity of 0.002. The saturated flow times used for generating Figure 12, 200 or 2,000 yr, are similar to the values of 196 and 1961 yr calculated using Equation 11. They were simply added to the unsaturated flow time for Case A to obtain total flow time to an accessible environment 2 or 10 km away from the repository (Figure 12, Cases B and C, respectively).

The scale of the plot in Figure 12 does not allow much discrimination between Cases A and C, or especially Cases A and B, so total flow times for Cases B and C are essentially the same as for Case A. Accordingly, total flow

time to an accessible environment 2 or 10 km away from the repository (Cases B or C) would be dominated by flow to the water table under expected conditions of flux through the unsaturated zone. Uncertainty about the total flow time is not sensitive to either definition of the accessible environment or to uncertainty about saturated flow conditions (Cases B and C).

Figure 13 shows groundwater travel times for the unlikely event that flux through the unsaturated zone exceeds 1 mm/yr. In this event, the flux would exceed the hydraulic conductivity of the matrix of the zeolitic Calico Hills unit, and this unit would be unable to pass all the water through matrix pores. The water in excess of about 1 mm/yr would be diverted horizontally through material with a horizontal conductivity corresponding to the excess flux until it encountered a zone, assumed to be a fracture, where the vertical conductivity is sufficient to pass the excess flux vertically to the water table. The vitric Calico Hills unit is able to vertically transmit all unsaturated flux up to several hundred millimeters per year through the matrix, so flow times from portions of the repository above the vitric unit would remain more than 10,000 yr even if flux exceeded 1 mm/yr. To move vertically through the zeolitic Calico Hills unit, water in excess of about 1 mm/yr would have to move down fractures with effective porosities much lower than the matrix (assumed for calculations to be 0.001 compared to 0.1 for the matrix). Flow time would be reduced correspondingly. The effects of this unlikely condition are shown in Figure 13 where the travel times for flux of up to 20 mm/yr are plotted.

Figure 13 indicates that groundwater flow time to the accessible environment is very sensitive to whether flux through the unsaturated zone can be transmitted by the matrix or whether it must move through fractures. If some flow in the unsaturated zone is entirely through fractures, flow time along

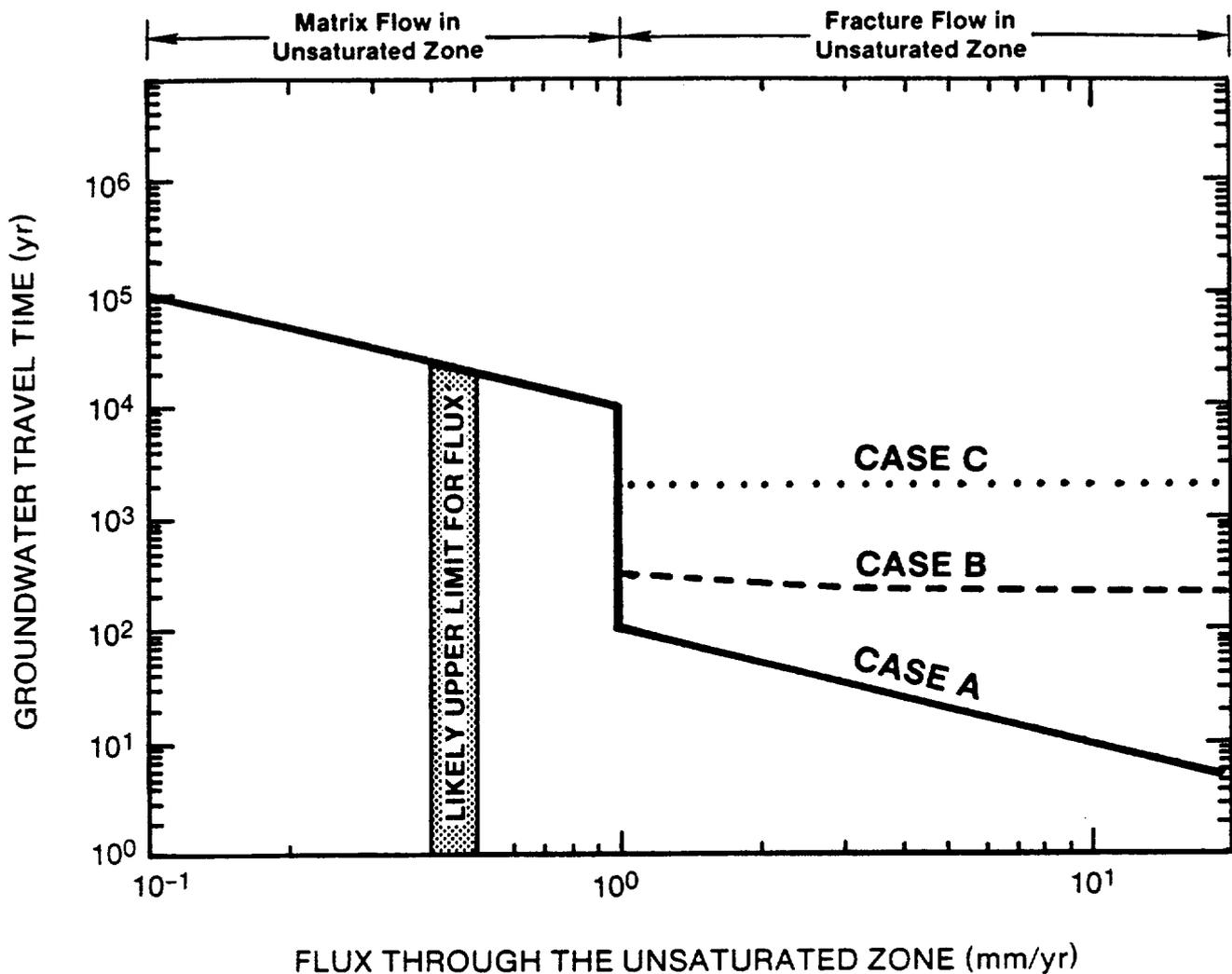


Figure 13. Groundwater flow times for Cases A, B, and C (see text) under unlikely conditions of flux up to 20 mm/yr; abrupt change in flow times at a flux of 1 mm/yr corresponds to a transition in the unsaturated zone between flow entirely in the matrix pores and flow in both fractures and matrix pores; flux greater than 1 mm/yr yields much shorter flow times through fractures in the unsaturated zone accounting for the abrupt change.

the fastest path to the accessible environment, i.e., through the zeolitic Calico Hills unit, would be dominated by saturated flow (Figure 13, Cases B and C). In this event, the accessible environment would have to occur several kilometers, perhaps the full 10 km, horizontally from the repository for the site to meet the 1000-yr flow-time requirement. As flux through the unsaturated zone increases, total flow time approaches flow time for the saturated zone alone. Accordingly, the value of effective hydraulic conductivity in the saturated zone is a major source of uncertainty about the total flow time if flux in the unsaturated zone exceeds the hydraulic conductivity of the matrix (compare Cases B and C, Figure 13).

In summary, it appears that the Yucca Mountain site easily satisfies the NRC and DOE requirements for a 1000-yr groundwater flow time to the accessible environment under the most likely conditions of flux through the unsaturated zone. This is true whether the accessible environment were to occur at the water table or at the end of either a 2- or 10-km flow path in the saturated zone, because flow time is likely to be dominated by slow percolation of water through the rock matrix in the unsaturated zone. Under unlikely conditions of unsaturated flux of more than about 1 mm/yr, flow time through the saturated zone would be the major component of total flow time.

The 1 mm/yr value for flux, above which significant fracture flow would occur, generally corresponds to the saturated hydraulic conductivity of the Topopah Spring and zeolitic Calico Hills units. Because the actual transition value varies within each unit and among different units, intervals of local fracture flow may be interspersed with intervals of local matrix flow. More widely distributed data are needed on both the vertical and the horizontal components of both saturated and unsaturated effective hydraulic conductivity of the rock matrix to allow more accurate characterization of this transition value throughout the unsaturated zone at Yucca Mountain.

## 4.2 Waste-Dissolution Rate

The performance objective addressed in this section is the limit on annual releases of waste from the engineered barrier system. The NRC codified this objective by setting a limit on predicted releases of 1 part in 100,000 of the inventory of each radionuclide constituting at least 0.1% of the total waste inventory calculated to be present 1000 yr after closure of the repository (Table 1). The engineered barrier system is defined by the NRC to include the waste package and the underground repository facilities (NRC, 1983).

Barriers to releases will be provided by waste packages and, for spent fuel, will include the uranium oxide itself, zircaloy cladding, stainless steel canisters necessary for waste handling, and any specially designed materials placed between the canisters and the emplacement holes in the rock. For disposal in the unsaturated zone, such packing materials might be designed to include air gaps that will inhibit by capillary processes the movement of water toward and away from the waste (Fernandez and Freshly, 1984; Winograd, 1981; Herzog et al., 1982; Roseboom, 1983). Artificial drainage channels might be designed within the underground facility to divert flowing water away from waste-emplacment areas (Roseboom, 1983). Other designed barriers might include some volume of rock around the waste packages and emplacement drifts. This volume will most likely be determined by a planned zone of sufficient heating and commensurate drying of the rock to cause moisture gradients that inhibit movement of liquid water toward the wastes (Pruess and Wang, 1983; Evans and Huang, 1983; Roseboom, 1983).

Compliance with the NRC's release limits will eventually be assessed by giving proper consideration to engineered barriers. The design details of these barriers are not available, so we cannot establish the outer boundaries

of the engineered-barrier system or the expected behavior within these boundaries. This leads us to adopt a conservative approach whereby no engineered barriers are assumed to be in effect and releases from the engineered-barrier system are controlled solely by the natural features of the site and the solubility of uranium, which constitutes most of the spent fuel.

Release rates are determined for this report by assuming that some part of the water intercepting the waste-emplacment area will contact the spent fuel and become saturated with uranium. We assume three cases for determining that amount of water:

1. All water flowing vertically to an area defined by the cross-sectional area of vertical emplacement holes will interact with the waste. This case is based on emplacement of 35,000 canisters about 65 cm in diameter in 35,000 holes 100 cm in diameter drilled into the floors of emplacement drifts. It leads to an assumption that 0.25% of the total flux passing through the repository level will interact with the waste. This case is slightly conservative in that 35,000 holes 100 cm in diameter would occupy somewhat less than 0.2% of the total repository area of about  $6 \times 10^6$  m<sup>2</sup>.
2. All water flowing vertically to an area defined by the cross-sectional area of horizontal emplacement holes will interact with the waste. This case is predicated on emplacement of multiple canisters in long, horizontal boreholes drilled into the walls of mined tunnels. It leads to an assumption that 2.5% of the total flux will interact with the waste. This percentage is also slightly conservative because a typical canister for spent fuel is 300 cm long,

yielding a total intercept area of 105,000 m<sup>2</sup> for 35,000 canisters placed in holes 100 cm in diameter. Compared to a total repository area of about 6 x 10<sup>6</sup> m<sup>2</sup>, this means that about 1.75% of the vertically moving flux would intercept the emplacement holes. Even if emplacement holes were twice as wide as the canisters (Jackson et al., 1984), only about 2.3% of the water flux would intercept the emplacement area.

3. All water flowing vertically to the area of mined openings will interact with the waste, a very conservative assumption in that some mechanism, currently unforeseen, would be required to concentrate flow as it moves through the repository. According to current information, quite the opposite would probably happen. Openings created by the repository, even if backfilled, would tend to act as capillary barriers, thus diverting flux away from, rather than into, excavated areas (Fernandez and Freshly, 1984). This case conservatively assumes that mining of repository drifts will remove about 25% of the rock at the level of the underground facilities. Thus, the total amount of water available to dissolve waste for this case is assumed to be 25% of the total flux passing through the repository horizon.

Simply, the three cases used for calculations are that 0.25%, 2.5%, or 25% of the water flowing through the repository level will interact with the waste. All three cases require some mechanism, as yet undiscovered, that would allow liquid water in the unsaturated zone to pass through voids in the waste emplacement holes so that contact with the waste canisters could occur. Thus, all three cases provide a highly conservative basis for estimating potential releases from the engineered-barrier system.

As outlined in Chapter 2, assumption 8, and described in Section 3.2.1, we assume that releases into the water are controlled solely by the solubility of uranium, which as an oxide makes up the matrix of the waste. We used a value for uranium solubility of  $4 \times 10^{-4}$  kg/m<sup>3</sup> of water to encompass current uncertainty about the actual value in the oxidizing environment that will exist near the wastes (see Section 3.2.1). The presence of zircaloy cladding, steel canisters, and packing materials may lower the Eh of water actually contacting the waste, resulting in lower solubilities. Because dissolution rates are assumed to be directly proportional to both uranium solubility and the amount of water contacting the waste, the three cases listed above for determining this amount may be construed also to represent three cases of uranium solubility for a given volume of interacting water. For example, if 2.5% of the total flux were to contact the waste, Case 1 would represent a uranium solubility of  $4 \times 10^{-5}$  kg/m<sup>3</sup>; Case 2,  $4 \times 10^{-4}$  kg/m<sup>3</sup>; and Case 3,  $4 \times 10^{-3}$  kg/m<sup>3</sup>.

The cladding and canister materials will tend to delay the penetration of corrosive surfaces to the waste itself, perhaps for thousands to tens of thousands of years in the low flux environment at Yucca Mountain (Oversby, 1983, McCright et al., 1983; Wilson and Oversby, 1984). Other waste-package components, such as air gaps, will inhibit contact of incoming water with the waste as well as inhibit movement of water carrying dissolved radionuclides away from the waste. Lower effective solubilities than we assume in this report are likely because of these engineered features as well as kinetic factors such as the development of weathering rinds around the unaltered spent fuel and rate-limited dissolution in droplets of water that may quickly run along the surface of the waste form. In addition, solubilities of many waste species, such as americium and plutonium, are less than for uranium (Kerrisk,

1984). Unless considerable separation of waste species from the fuel matrix has occurred, species with solubilities higher than uranium probably will not be released to solution until the uranium matrix dissolves enough to allow water contact with individual particles of these species (Braithwaite, 1984). The rate of dissolution of uranium thus constrains the individual dissolution rates of these species, assuming they are not significantly concentrated on exposed surfaces of the spent fuel.

Though we cannot precisely identify the actual conditions that will occur at the water-waste contact, these conditions should tend to slow dissolution rates relative to those determined solely by the solubility of uranium. By allowing water to overcome capillary barriers and begin dissolving the wastes and by assuming releases are based on a high solubility for uranium, we are being highly conservative, perhaps to the point of seriously overestimating waste dissolution in a repository at Yucca Mountain. However, such an approach can point to the unique qualities of the site, independent of engineered features, which will contribute to waste containment.

Results of our calculations for expected flux through the unsaturated zone of less than 1 mm/yr are shown in Figures 14 and 15. Figure 14 shows the annual volume of water contacting the waste and the corresponding mass of dissolved waste for the three cases of presumed contact area. Figure 15 shows the ratio of the annually dissolved mass to the total mass of waste in the spent fuel. This ratio is nearly constant in time and does not significantly depend on the period of complete containment. Figure 15 indicates that annual releases will constitute only about 1 part in  $10^8$  of the total mass of the spent fuel, even under the highly conservative case where 25% of a total flux of 1 mm/yr is assumed to interact with the waste. For unlikely flux values up to 20 mm/yr, which encompass and probably exceed credible amounts of flowing

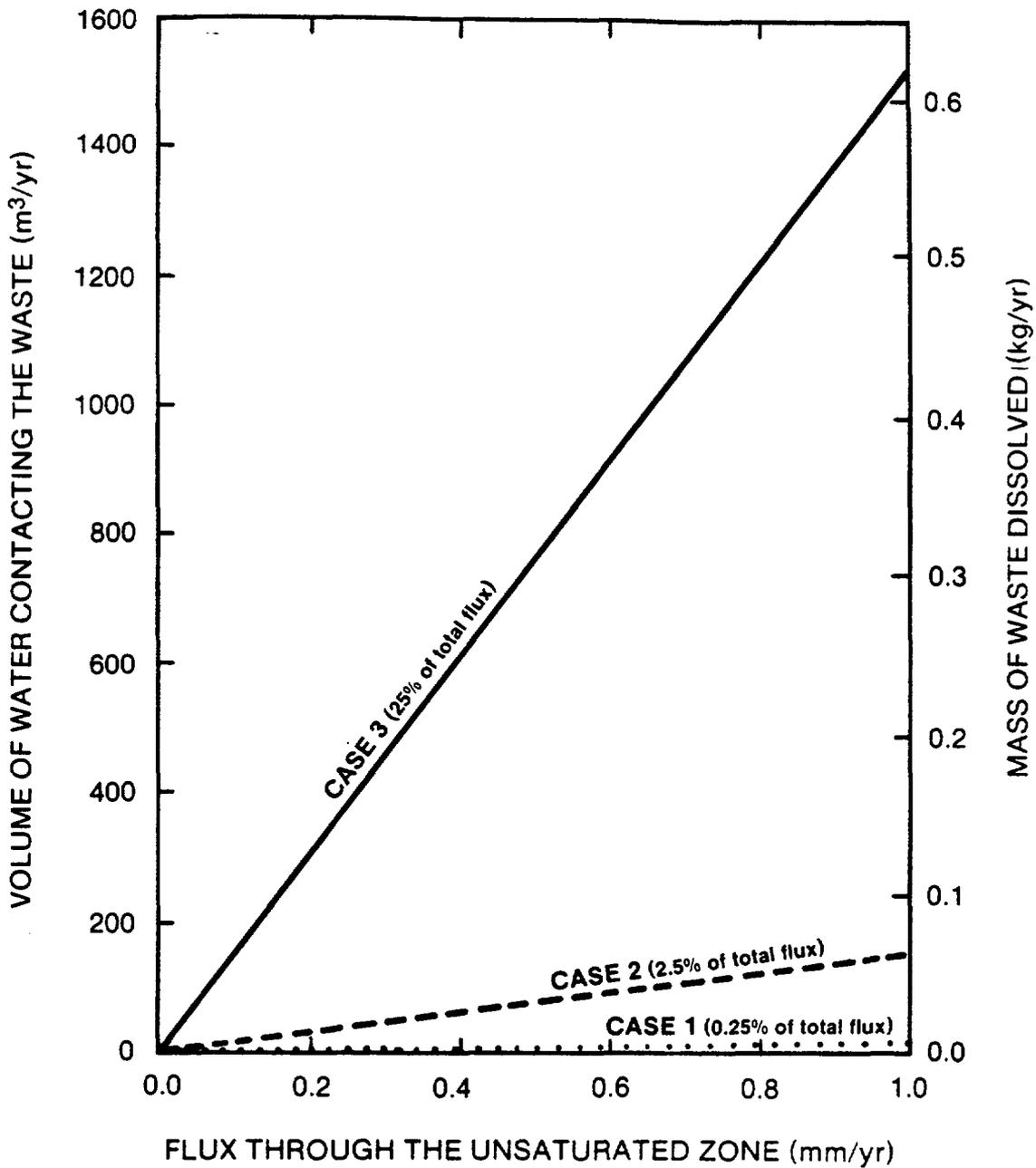


Figure 14. Annual volume of water contacting all of the waste in the repository and the corresponding total amount of waste dissolved for a uranium solubility of  $4 \times 10^{-4}$  kg/m<sup>3</sup> of water as a function of flux up to 1 mm/yr through the unsaturated zone; Cases 1, 2, and 3 represent different amounts of total flux interacting with the waste (see text); the three cases also may be interpreted to represent order-of-magnitude variations in uranium solubility for a single amount of interacting water.

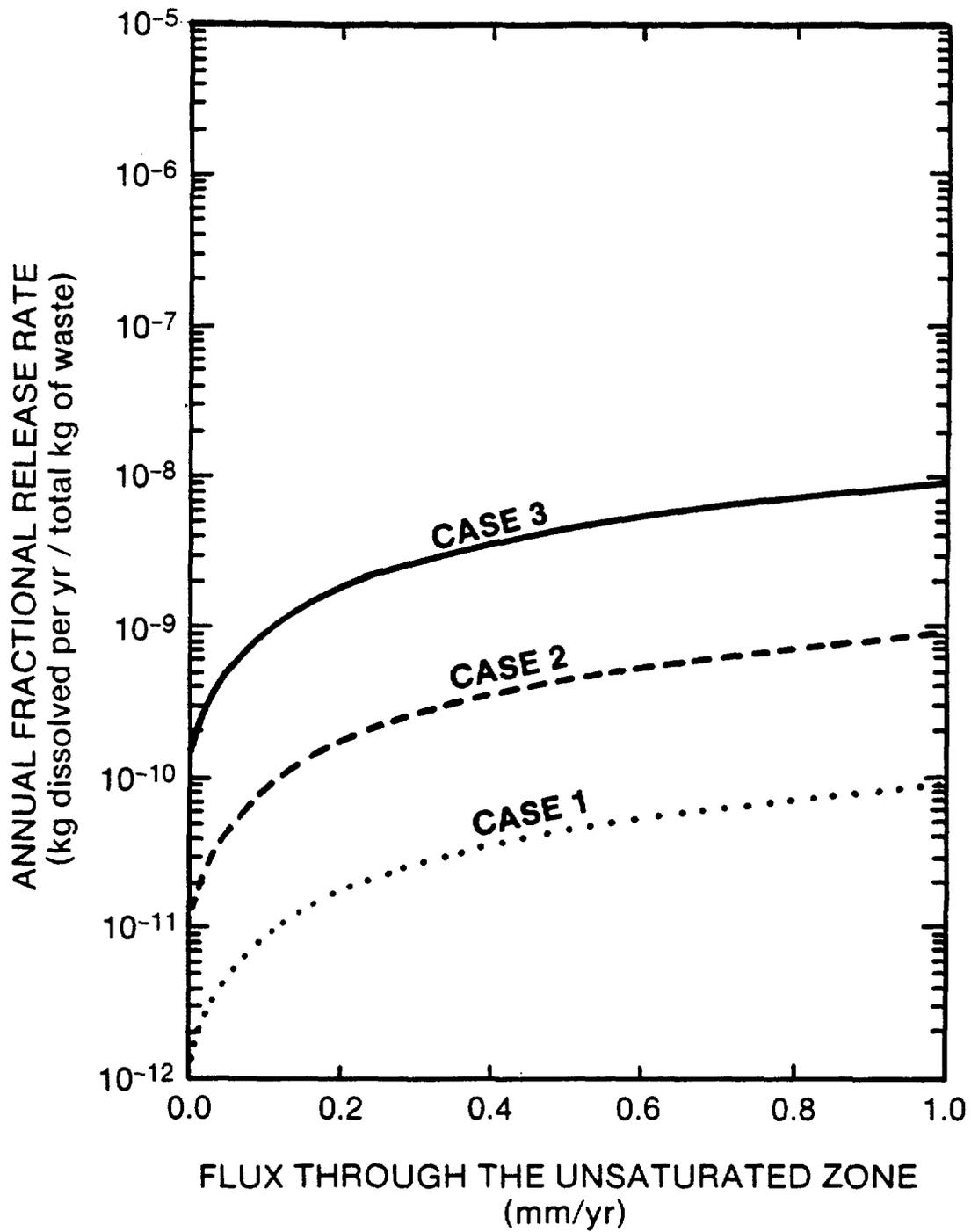


Figure 15. Annual mass-fraction of radionuclides dissolved at the repository by flux through the unsaturated zone of less than 1 mm/yr; Cases 1, 2, and 3 represent different amounts of the total flux interacting with the wastes (see text).

water that might be caused by climatic changes, the annual mass releases would still be less than 1 part in  $10^6$  (Figure 16).

Annual release rates, in terms of mass fraction,  $R$ , were calculated from

$$R = \frac{q \cdot s_u}{m_u(t)} \cdot G(t) \quad (\text{kg/yr}) \quad (12)$$

where  $q$  is the annual volume of water contacting the wastes in  $\text{m}^3$ ,  $s_u$  is the solubility of uranium in  $\text{kg}/\text{m}^3$ ,  $m_u(t)$  is the total mass in kg of uranium in spent fuel at time  $t$ , and  $G(t)$  is a function representing the history of containment. Assuming congruent leaching, the fractional release of mass for individual radionuclides is the same as for uranium (see Equations 10 through 14, Appendix A). Because the mass of uranium is dominated by U-238 with a half-life of nearly 5 billion years, the fractional release rate is essentially constant in time, assuming  $q$  and  $s_u$  are constant and  $G(t)$  equals 1. This constancy holds only when  $q$  times  $s_u$  is very small compared to  $m_u(t)$ , so mass loss of  $m_u(t)$  is negligible over the time period of concern. Because uranium mass in the spent fuel is essentially constant for the flux and uranium solubility used in our calculations, any arbitrary total mass of the spent fuel, as a function of time less than about 1,000,000 yr, yields essentially the same fractional release rate. We arbitrarily chose uranium mass at 10 yr after removal from the reactors ( $t = 10$  yr from Table 1) to calculate fractional releases.

Figure 17 expresses the mass-dissolution rates another way. In this figure the total time required to dissolve all spent fuel in a repository is plotted for the likely range of flux, i.e., up to 1 mm/yr. This figure suggests that billions of years would be required to dissolve all the waste in a

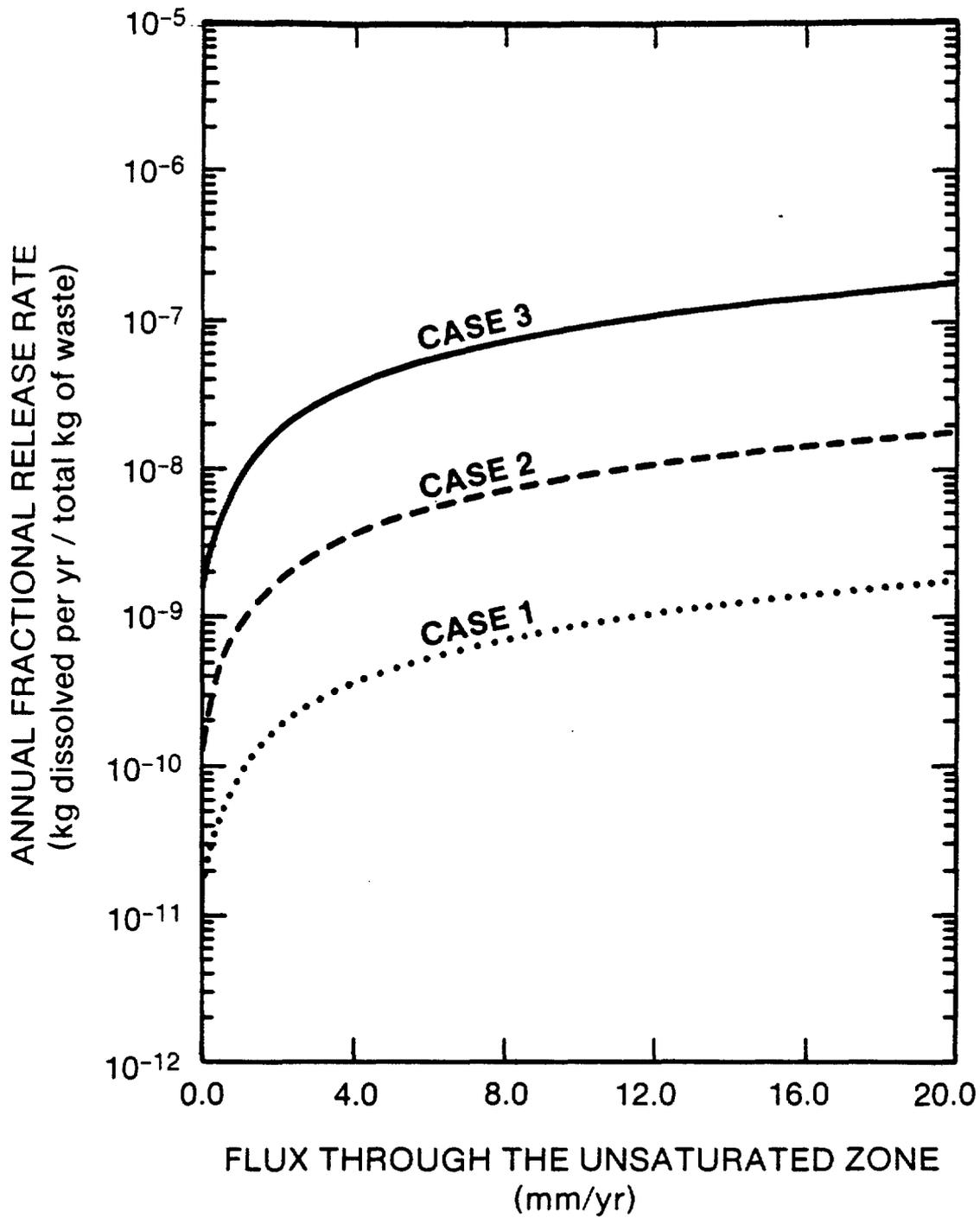


Figure 16. Annual mass-fraction of radionuclides dissolved at the repository by flux of up to 20 mm/yr; Cases 1, 2, and 3 represent different amounts of the total flux interacting with the wastes (see text).

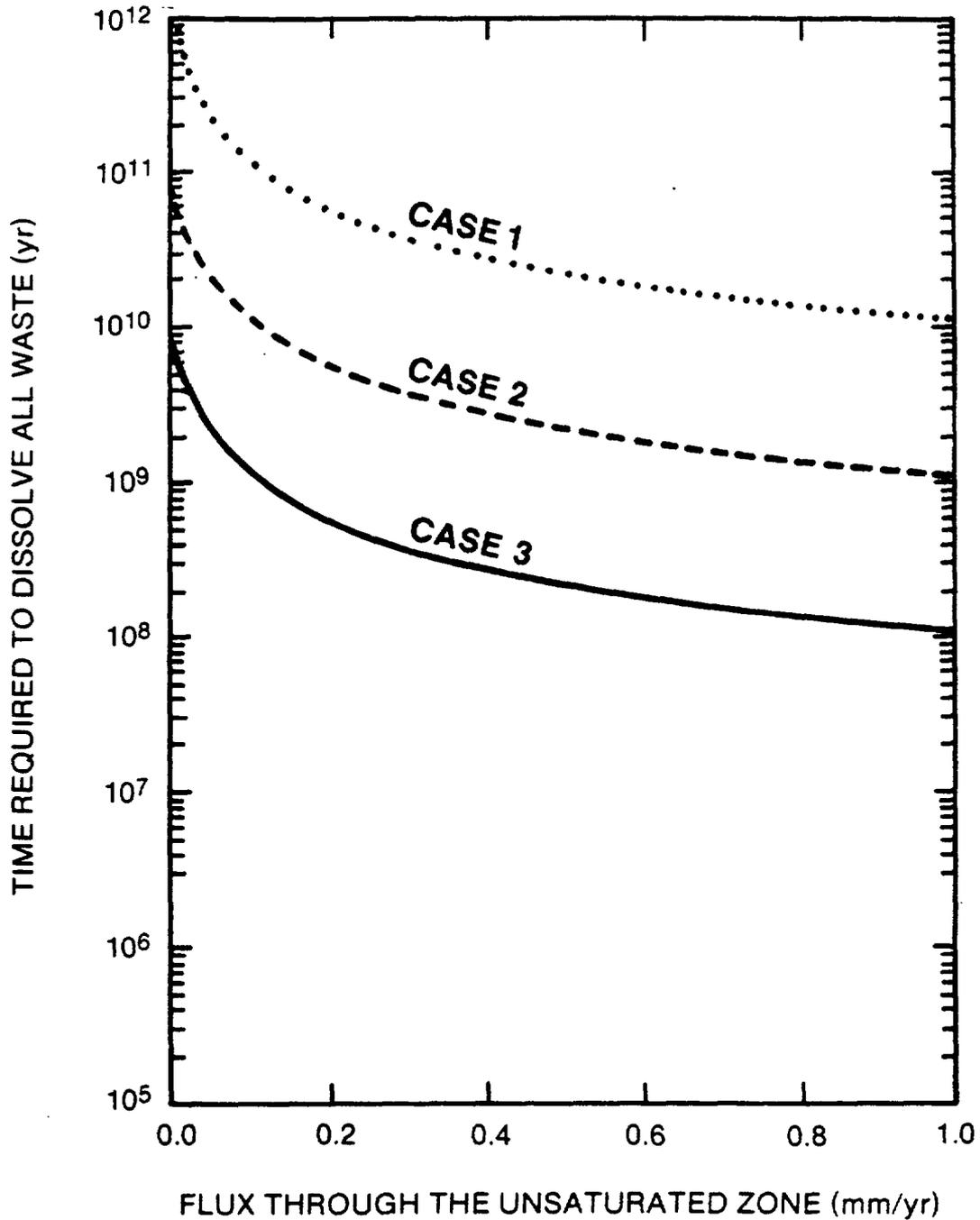


Figure 17. Total time required to dissolve all waste in a repository at Yucca Mountain if current conditions prevail; Cases 1, 2, and 3 represent different amounts of the total flux interacting with the wastes (see text).

repository if current conditions prevailed. Of course, site conditions will change, perhaps dramatically, over such long times, and the wastes will have decayed to insignificant levels of radioactivity. The predicted total leach times are shown only to indicate the very slow releases expected during the next tens to hundreds of thousands or perhaps millions of years during which conditions will probably remain grossly similar to those occurring today.

Release rates shown in Figures 14 through 17 are based implicitly on an assumption that all waste packages fail instantaneously, simultaneously, and completely, i.e., release wastes to the limit set by uranium solubility. This is represented mathematically by assigning a value of 1 to  $G(t)$  in Equation 12. A more realistic scenario is that most packages will completely contain all wastes for a given time but a few will have slight flaws that allow small amounts of waste to escape as soon as water contacts the canisters. As time progresses, more packages are likely to fail (i.e., begin releasing their contents), and maximum rate, determined by uranium solubility, is reached. This process of progressively decaying containment may be represented by  $G(t)$  in Equation 12, describing a constant failure rate that is the reciprocal of the time during which 63% of the canisters have failed, referred to as the mean time-to-failure. The corresponding release rate would be proportional to a cumulative distribution in time (see Appendix A, Equation 9). Because we do not know the proper description of waste-package performance, we chose a simple exponential distribution with a mean time-to-failure of 10,000 yr, a conservative time required to corrode the stainless steel canisters and zircaloy cladding that will surround and protect the spent-fuel matrix.

Figure 18 compares the trends of fractional release rates of waste mass for progressively decaying waste packages and for waste packages that are 100% effective until complete failure 300 or 1000 yr after repository closure.

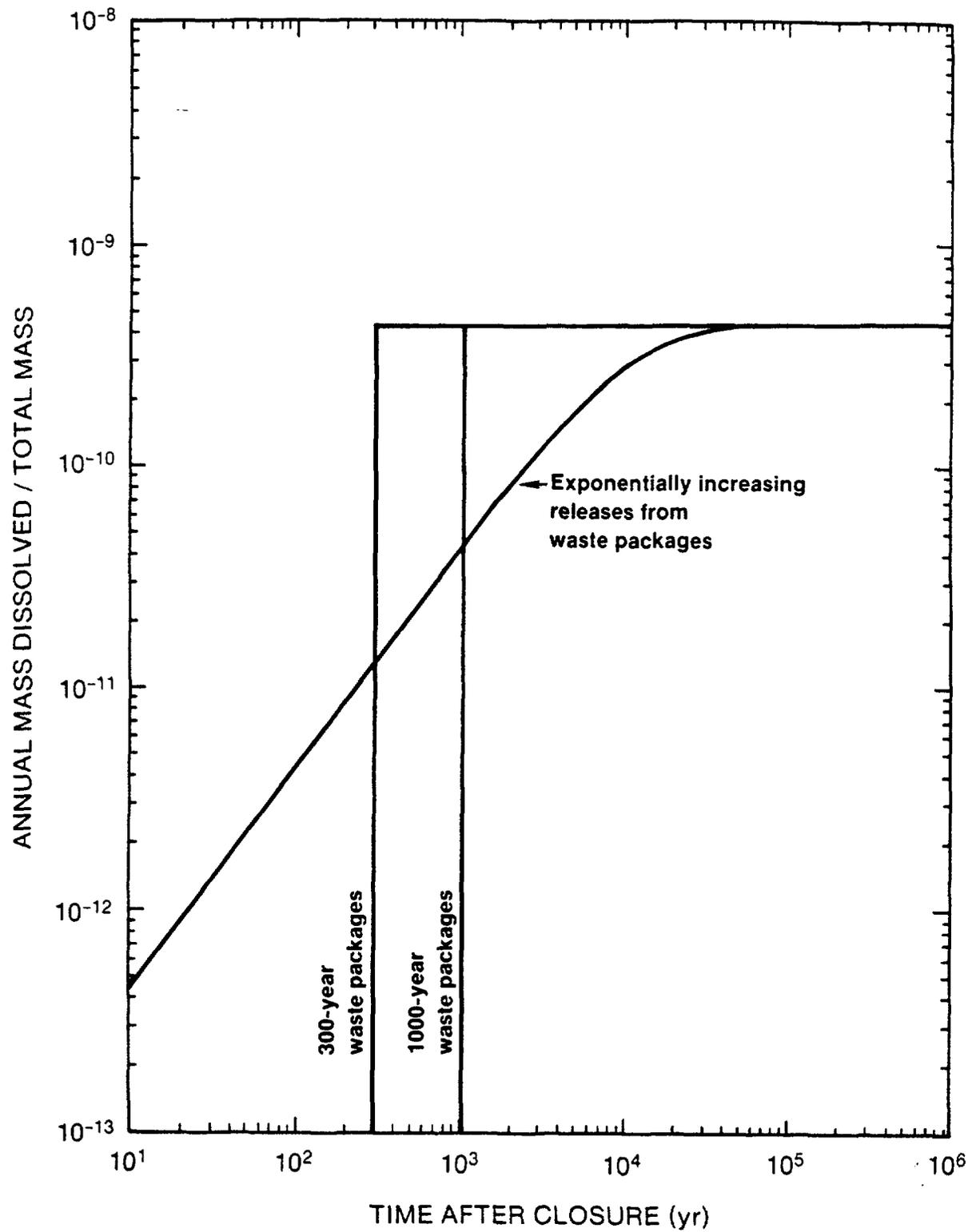


Figure 18. Annual mass-fraction of waste dissolved as a function of time by 2.5% of a total flux of 0.5 mm/yr for 300- and 1000-yr waste packages and packages with an exponentially increasing loss of containment.

Though all radionuclides will begin to dissolve earlier than for waste packages that achieve complete containment for 300 or 1000 yr, the early mass releases caused by progressive failure will be negligible because of the initial limited failure rate. If complete containment for 300 or 1000 yr were achieved in conjunction with subsequent progressive failure, initial mass releases might be limited to a few percent of releases from instantaneously failing packages (Figure 18). Mass releases would then remain lower until several tens of thousands of years after closure, when they finally would converge with release rates determined solely by uranium solubility. In short, progressively decaying waste packages may allow releases to begin sooner but will limit them to levels well below those based on either 300- or 1000-yr waste packages for several decamillenia.

The concept of progressive waste-package decay is based on understanding of the likely site conditions at Yucca Mountain and does not rely on any special engineered features other than those that already exist, i.e., zircaloy cladding, or are necessary to handle and emplace the waste in a repository, i.e., a steel canister. The behavior of these materials in the low flux through the repository will probably restrict releases from the waste packages to some kind of distribution, such as the assumed exponential distribution. The exact form of the leaching model for Yucca Mountain remains to be determined.

We adopted an approach for Figure 18 that assumed some canisters would partially fail immediately after repository closure. This approach is likely to overestimate early releases because the thermal field around the wastes may prohibit flow away from the emplacement holes for several hundred years. In addition, voids within the emplacement holes will probably act as effective capillary barriers that will prohibit water from moving from the rock to the

waste canisters. As a result, Figure 18 is not intended as a projection of actual releases stemming from an actual set of waste packages that will be emplaced at Yucca Mountain. Rather, the purpose of Figure 18 is to point out that the expected releases from the repository will probably be less than indicated by adopting an unrealistic assumption that all waste packages fail completely and simultaneously either 300 or 1000 yr after repository closure. The likely corrosion rate of canisters in the low flux at Yucca Mountain makes such failure modes highly unrealistic.

Figures 14 through 18 show annual fractional releases of the total mass of the waste in spent fuel and cannot be compared directly to the NRC release-rate limits, which are expressed in terms of curies. To compare annual curie release rates to the NRC limits, the annual mass releases in kg/yr of individual radionuclides must be multiplied by the specific activity expressed as Ci/kg. This number, in Ci/yr, can then be divided by the NRC release-rate limit for each radionuclide given in Table 1 to assess how well the Yucca Mountain site is expected to comply with the NRC requirements.

Figure 19 shows curie release rates for individual radionuclides and the integrated rate for all radionuclides normalized so that the NRC limits are set to equal 1. This figure is based on an unrealistic assumption that waste dissolution begins immediately after closure of the repository and continues unabated except by the solubility of uranium and the volume of water contacting the waste. Two-and-one-half percent of a total flux of 0.5 mm/yr is assumed to react with the waste. The releases shown on Figure 19 are unrealistically conservative during the early times when releases of short-lived cesium and strontium would be near the NRC release limits. By 300 yr after closure, a conservative initial time for any releases, these fission products would be reduced by radioactive decay to the extent that they would be

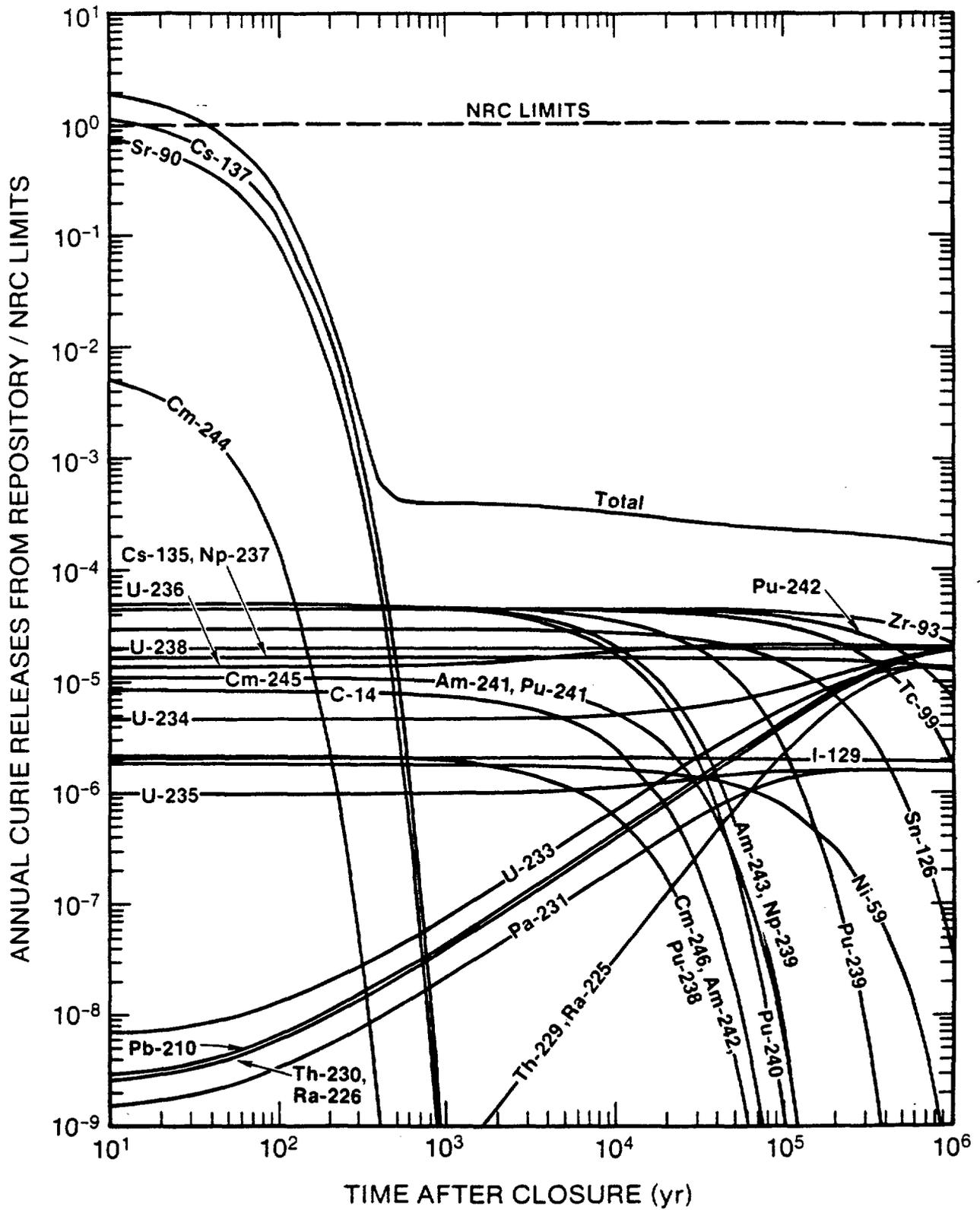


Figure 19. Ratio of the NRC release-rate limits of curies dissolved at the repository by 2.5% of a total flux of 0.5 mm/yr; release ratios shown for individual radionuclides (lower curves) and all radionuclides in combination (upper curve).

released at only one thousandth of the release-rate limit. Curium-244 also would be released at relatively high rates during the first 100 yr after closure, assuming no containment, because of its high specific activity. In combination, these three radionuclides would dominate the early total releases shown by the upper curve on Figure 19 if no containment period were in effect.

After about 400 yr, total release rates would remain nearly constant for at least 1 million yr, indicating the negligible effect that complete containment for an arbitrary period longer than about 400 yr would have on eventual release rates. The longer-term, nearly constant total release rate, about one thousandth of the sum of the NRC limits for individual radionuclides, would be dominated for about 10,000 yr by long-lived isotopes of carbon, cesium, technetium, zirconium, tin, plutonium, uranium, americium, neptunium, and curium. Each of these elements would contribute more than 1% to the total release rate vis-a-vis the NRC limits. Release rates of several nuclides, including C-14, Pu-239, Pu-240, Pu-242, Cm-245, Am-241, Am-243, and Cm-246, would decay to negligible levels during the first 100,000 yr following closure, whereas release rates of U-233, Ra-225, Ra-226, Pb-210, and Th-229 would increase to more than 1% of the total by 1 million yr after closure. Several nuclides, including Ni-59, I-129, U-235, and Pu-242 would never exceed more than about 0.1% of the total release rate. In no case would the release rate of a single radionuclide exceed one ten-thousandth of the NRC limit during the first million years. The relatively large releases of zirconium, plutonium, and americium nuclides shown on Figure 19 probably overstate likely releases, because these elements will probably be much less soluble than uranium in a repository environment at Yucca Mountain (Kerrisk, 1984). Our assumption that they will leach congruently with uranium results in projected releases that do not account for their low solubilities.

The ratio of total-curie releases to the sum of the NRC limits for individual nuclides is shown in the upper curve of Figure 19. Figure 20 compares this measure for 300-yr, 1000-yr, and exponentially decaying waste packages. Any of these forms of waste package behavior would limit the initial high release rates indicated on Figure 19 to levels well below the NRC limits by prohibiting or inhibiting releases of short-lived nuclides.

Yet another way to express expected performance at the repository is shown in Figure 21. This figure plots a three-dimensional representation of the ratio of cumulative curies dissolved and remaining in solution at any given time to the EPA release limits as a function of the likely range of flux through the unsaturated zone. For more likely cases where 0.25 or 2.5% of the total flux would contact the waste (see left and right axes, respectively, on Figure 21), the total curies outside the waste packages at any point in time would remain less than a few percent to a few tenths of a percent of the proposed EPA release limits. For flux less than 1 mm/yr and complete containment for 300 yr (the basis for Figure 21), total curies remaining in solution will never exceed the EPA cumulative release limits, even if 25% of the total flux interacts with the wastes (rear axis, Figure 21). Figure 21 indicates that low flux through the unsaturated zone at Yucca Mountain will ensure slow enough waste dissolution that compliance with the EPA standard would probably occur even if the standard were applied at the repository itself.

In summary, it appears that even without engineered barriers a repository at Yucca Mountain would easily comply with the NRC requirements for slow releases of wastes from the engineered-barrier system. If engineered barriers were considered, including specially placed capillary barriers, steel canisters, zircaloy cladding, repository drainage systems, and heat-induced moisture gradients, only an insignificant amount of water, or no water at all,

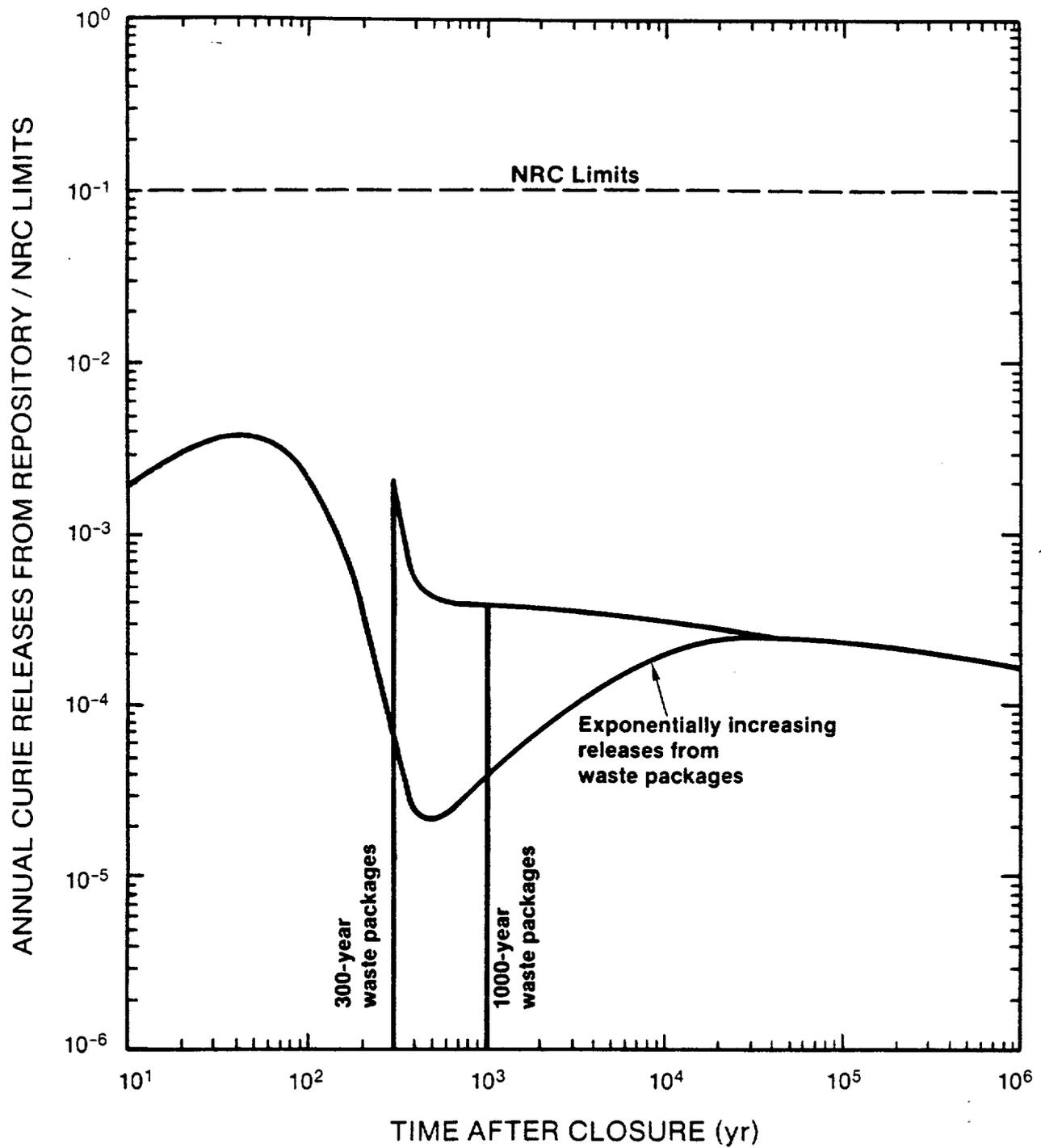


Figure 20. Ratio of the sum of NRC release rate limits for individual radionuclides of total curies dissolved at the repository by 2.5% of a total flux of 0.5 mm/yr for 300- and 1000-yr waste packages and packages with an exponentially increasing loss of containment.

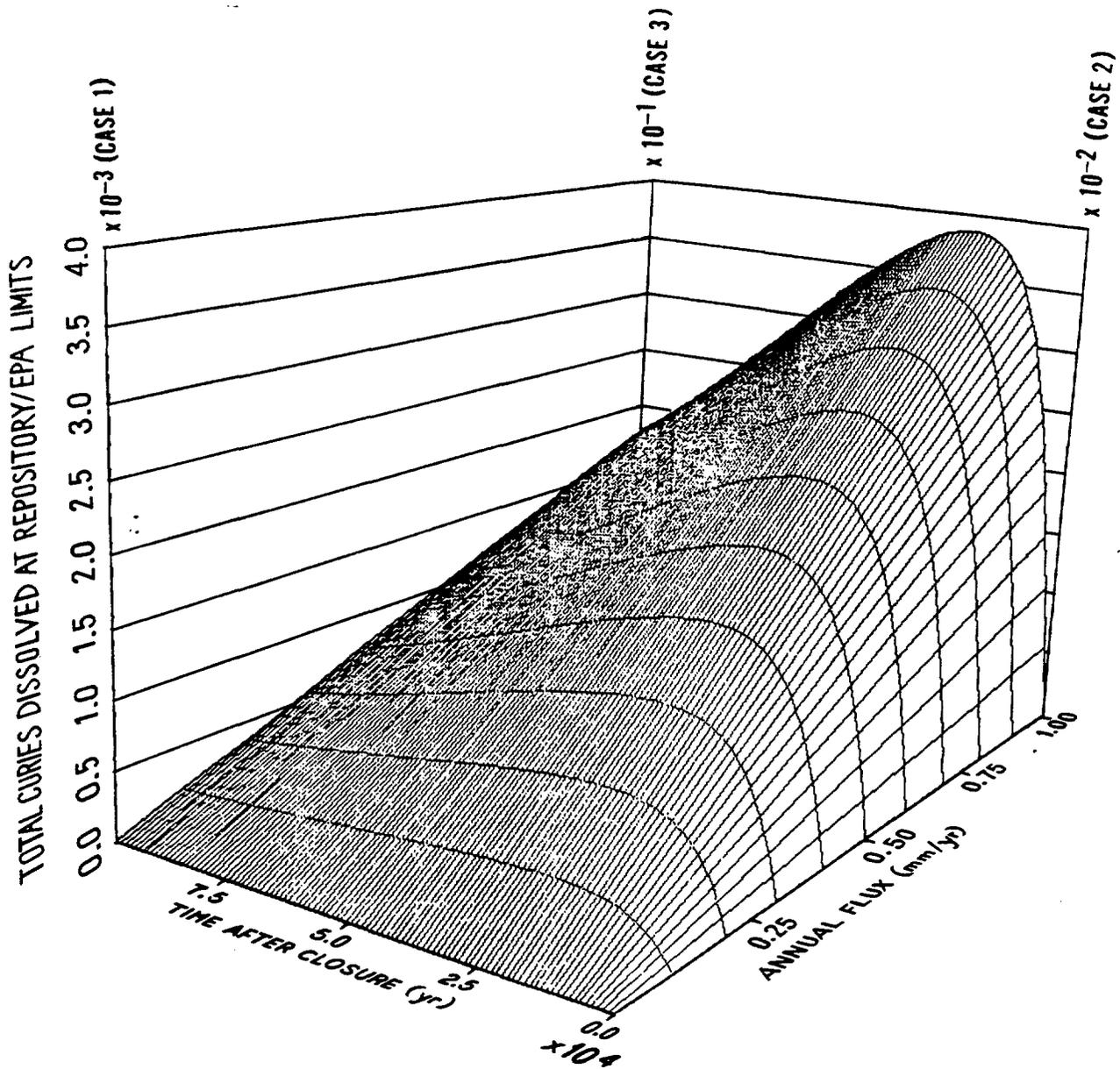


Figure 21. Ratio to the EPA limits of total curies dissolved at the repository by a total flux of up to 1 mm/yr; three cases for different amounts of the total flux contacting the waste are represented by the three vertical axes of the graph (left vertical axis for Case 1 or 0.25% of the total flux, right axis for Case 2 or 2.5%, and rear axis for Case 3 or 25%); plot assumes complete containment for 300 yr and accounts for the decay of radioactivity after the wastes have dissolved.

would contact the waste. Actual release rates, therefore, are likely to be negligible. Simply, the amount of water flowing at Yucca Mountain is so low that release rates, in all likelihood, will be very slow and well within the limits set by the NRC.

#### 4.3 Releases to the Accessible Environment

The EPA will provide the environmental standards against which predictions of repository performance ultimately will be judged. The current proposed standards limit the total curies that may be released to the accessible environment during the next 10,000 yr, as discussed in Section 1.2 (EPA, 1982; 1984). The allowable releases are expressed in curies per 1000 MTHM (Table 1).

To address these standards we assumed that all waste dissolved at the repository, as established in Section 4.2, is transported from the disturbed zone toward the accessible environment by groundwater moving at rates established in Section 4.1. Flow within the disturbed zone is also considered, consistent with the EPA proposed regulations, which do not recognize a distinction based on the disturbed zone. Optional locations of the accessible environment are assumed to be the same as defined for groundwater travel time, i.e., at the water table and at the end of 200- and 2000-yr flow paths in the saturated zone. Geochemical retardation is assumed to slow radionuclide movement relative to groundwater flow according to the principles discussed in Section 3.2.2.

The values of retardation used for individual radionuclides are shown in Table 6. These values were applied to all rock types occurring along two flow paths through the unsaturated zone considered in our analyses (Figure 3). Matrix retardation was used for all portions of flow paths through the vitric

Table 6. Sorption values of radionuclides in tuff matrix, Kd, and fractures, Ka, and corresponding retardation factors, Rd, used for calculations of radionuclide movement relative to groundwater flow.

Element	Kd (cm <sup>3</sup> /g)(1)	Ka (g/cm <sup>2</sup> )(4)	Rd for Matrix		Rd for Fractures	
			Zeolitic(5)	Vitric(6)	Unsaturated(7)	Saturated(8)
Am	180	1.8 x 10 <sup>-4</sup>	3600	1800	1.4	1.0
C	0	0	1	1	1.0	1.0
Cm	180	1.8 x 10 <sup>-4</sup>	3600	1800	1.4	1.0
Cs	290	2.9 x 10 <sup>-4</sup>	5800	2900	1.5	1.0
I	0	0	1	1	1.0	1.0
Ni	100(2)	1.0 x 10 <sup>-4</sup>	2000	1000	1.2	1.0
Np	7	7.0 x 10 <sup>-6</sup>	140	71	1.0	1.0
Pa	64	6.4 x 10 <sup>-5</sup>	1300	640	1.1	1.0
Pb	5(2)	5.0 x 10 <sup>-6</sup>	100	51	1.0	1.0
Pu	64	6.4 x 10 <sup>-5</sup>	1300	640	1.1	1.0
Ra	900(3)	9.0 x 10 <sup>-4</sup>	18000	9000	2.8	1.2
Sn	170	1.7 x 10 <sup>-4</sup>	3400	1700	1.3	1.0
Sr	53	5.3 x 10 <sup>-5</sup>	1100	530	1.1	1.0
Tc	0.3	3.0 x 10 <sup>-7</sup>	7	4	1.0	1.0
Th	580(2)	5.8 x 10 <sup>-4</sup>	12000	5300	2.2	1.1
U	1.8	1.8 x 10 <sup>-6</sup>	37	19	1.0	1.0
Zr	500(2)	5.0 x 10 <sup>-4</sup>	10000	5000	2.0	1.1

- (1) Unless otherwise indicated, distribution coefficients were inferred from sorption ratios given by Daniels et al. (1982, 1983).
- (2) Inferred from midrange retardation factor for tuffs in compilation by Krauskopf, Table 7-1, National Research Council (1983).
- (3) Barium used as chemical analogue for radium (Daniels et al., 1983).
- (4) Calculated from Kd using surface area given by Daniels et al. (1982).
- (5) Calculated from Eq (7) using  $\gamma = 2$ ,  $n = 0.1$ .
- (6) Calculated from Eq (7) using  $\gamma = 2$ ,  $n = 0.2$ .
- (7) Calculated from Eq (10) using  $b = 10$  m.
- (8) Calculated from Eq (10) using  $b = 100$  m.

part of the Calico Hills unit for all conditions of flux, and through the zeolitic Calico Hills unit for flux less than 1 mm/yr, the likely threshold value for matrix flow. For flux greater than 1 mm/yr, fracture retardation was used along all portions of the flow path passing through the zeolitic Calico Hills unit. The matrix values on Table 6 generally correspond to the lowest sorption value listed on Table 5 for rock types occurring along the flow paths of interest; the fracture values were calculated from the lowest sorption values. This procedure provides a simple, but conservative, basis for calculating radionuclide transport through the rocks at Yucca Mountain.

#### 4.3.1 Bounded Releases to the Water Table under Expected Site Conditions

Figure 22 shows the calculated ratio of curies released at the water table during the next 100,000 yr to the EPA's release standards for flux up to 1 mm/yr. This figure indicates that no releases to the accessible environment should occur during the 10,000-yr period of compliance with the EPA standard, even if the accessible environment occurs at the water table directly below the repository. A reasonable upper limit on flux of 0.5 mm/yr (see Section 3.1.2) is highlighted on Figure 22. Figure 23 shows cumulative releases from the repository (upper line) and to the water table (lower lines) for this flux, including the contributions of individual radionuclides to releases at the water table. The area between the upper curve and lower set of curves on Figure 23 represents the isolation potential provided by the unsaturated zone.

For 0.5 mm/yr flux, groundwater travel time from the disturbed zone to the water table will be about 20,000 yr (Figure 12). It follows that no radionuclides would reach the water table for about 30,000 yr after closure of the repository (Figures 22 and 23). The additional 10,000 yr represents a

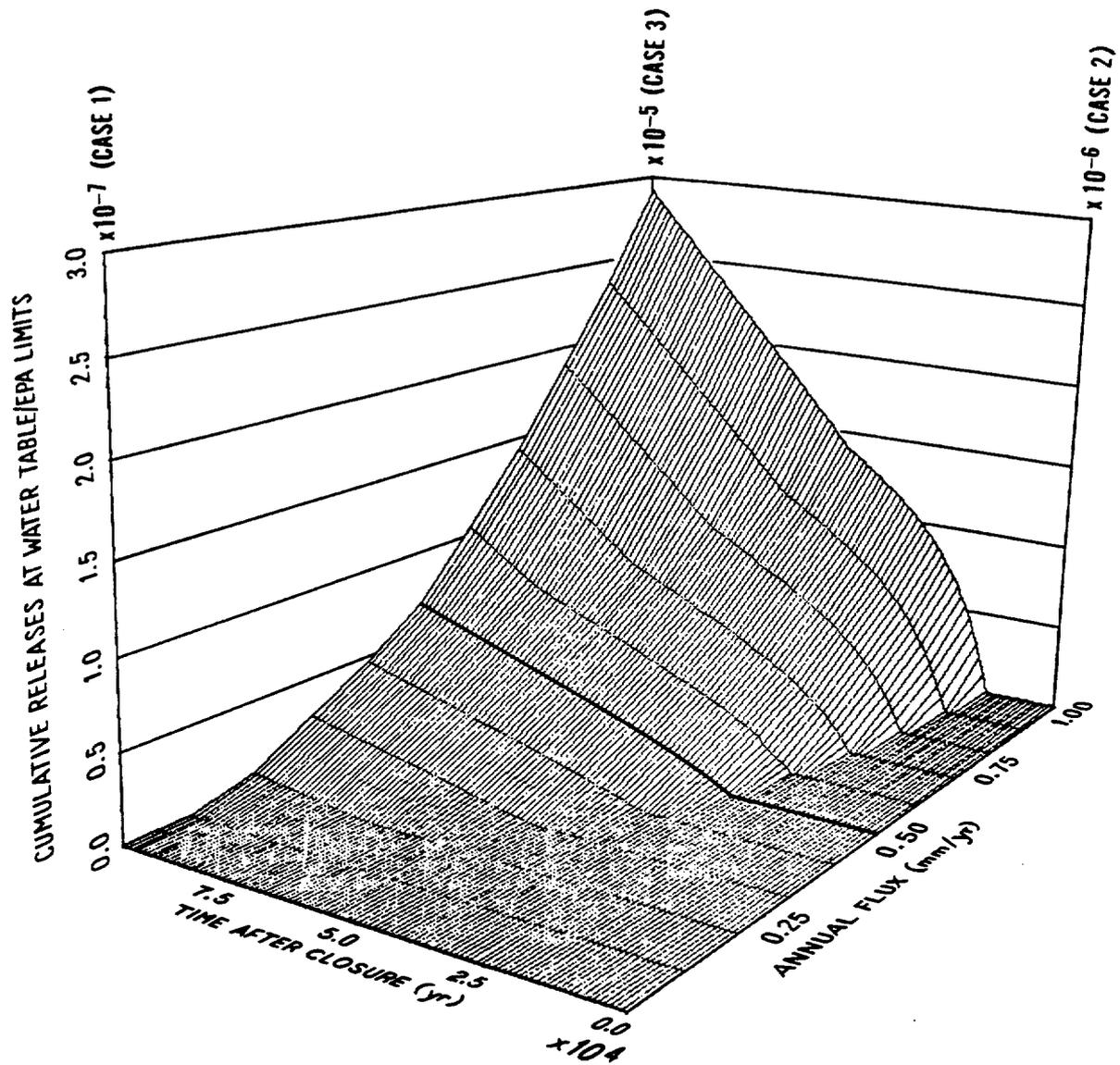


Figure 22. Ratio to the EPA limits of total cumulative curies reaching the water table during the 10,000 yr after repository closure for flux through the unsaturated zone of up to 1 mm/yr; three separate vertical axes show release ratios for three cases of the amount of the total flux contacting the wastes (see text); the three axes also may be interpreted to represent order-of-magnitude variations in uranium solubility for a single amount of interacting water; heavy line accentuates expected upper bound on flux of 0.5 mm/yr; 300-yr waste packages assumed.

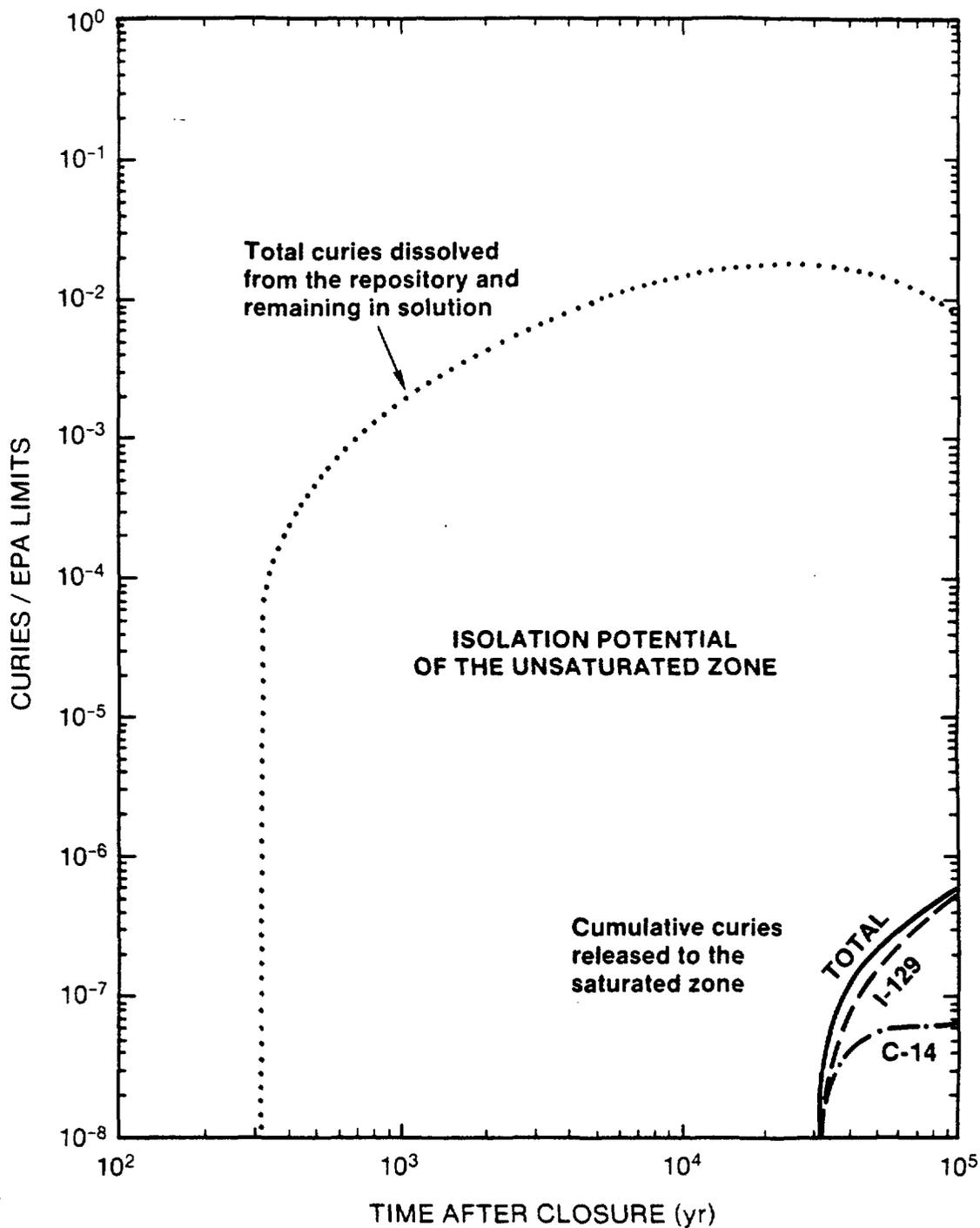


Figure 23. Ratio to the EPA limits of total cumulative curies and curies of individual radionuclides reaching the water table (low curves) and total curies dissolved at the repository and remaining in solution (upper curve) during the 100,000 yr after repository closure for a total flux of 0.5 mm/yr and contact with the waste of 2.5% of this total flux (see right hand axis, Figure 22); the total-curie curve corresponds to the line accentuating 0.5 mm/yr flux on Figure 22; 300-yr waste packages assumed.

300-yr period of complete containment within the waste packages and, more significantly, groundwater travel time from the repository to the edge of the disturbed zone. The disturbed zone is defined as in Section 4.1 to occur at the base of the vitrophere about 50 to 100 m below the proposed repository level (Figure 11).

For a conservative assumption that 2.5% of the total flux would interact with the waste (right-hand axis Figures 22 and Figure 23), total cumulative releases for a flux of 0.5 mm/yr during the next 100,000 yr would constitute only about  $10^{-6}$  (one millionth) of the allowable releases. However, cumulative releases are the basis of compliance with the EPA standards only during the first 10,000 yr following repository closure. We concur with the National Research Council (1983) that the curie release limits based on population dose, as proposed in the current EPA standards, are not ideal surrogates for estimating health effects cause by a repository. However, if the standards must be used, a more reasonable surrogate for assessing the potential hazards after 10,000 yr would be the total curies remaining in the accessible environment, not cumulative curies released to it. This alternative measure of hazards accounts for decay of radioactivity and thus approximates the potential health protection required by the EPA stand excess of 10,000 yr.

Figure 24 shows curies remaining in solution in the saturated zone during the first 100,000 yr, assuming a flux of 0.5 mm/yr. The cumulative curies released to the accessible environment from Figure 23 are shown on Figure 24 for comparison. Only two radionuclides, I-129 and C-14, are projected to reach the water table 100,000 yr after repository closure (Figures 23 and 24). The I-129 is the dominant contributor to the minuscule total releases because, by assumption, it is unretarded and its half life, about 17 million years,

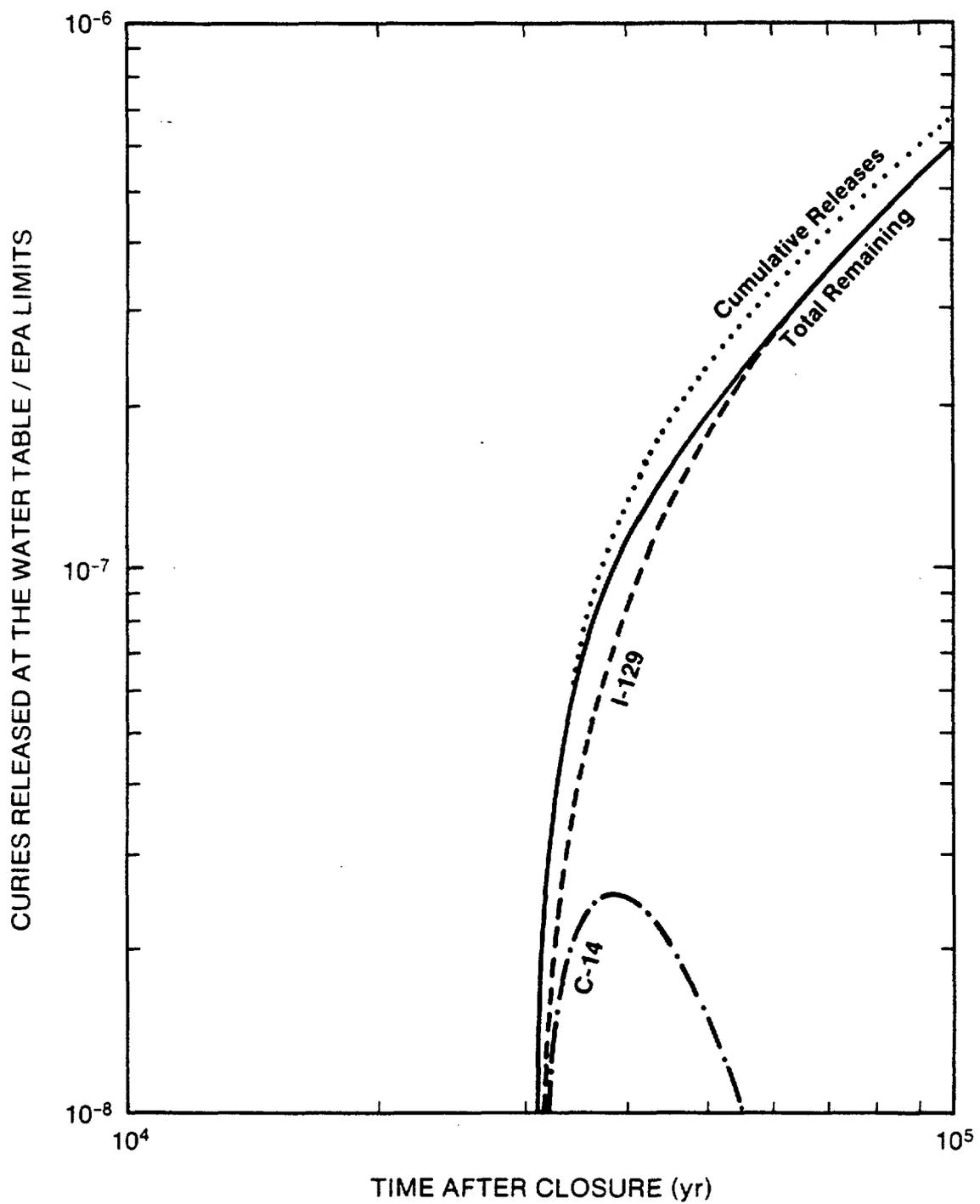


Figure 24. Ratio to the EPA limits of total curies and curies of individual radionuclides remaining below the water table for the same condition as Figure 23; upper curve shows total cumulative curies released to the water table and, for comparison, is the same as the cumulative release curve on Figure 23 (note change in scale of the axes).

is much longer than the period for which the releases were calculated. The initial inventory of I-129 in 1000 MTHM of 10-yr old spent fuel is about 33 Ci, whereas 1000 Ci are allowed to be released during the first 10,000 years after closure (Table 1). Thus, the only radionuclide calculated to be released in discernible amounts never exceeds the release standards, even at the time of emplacement in the repository. Carbon-14, the only other nonretarded species, will arrive at the water table simultaneously with iodine, about 30,000 yr after closure for a flux of 0.5 mm/yr. However, because its half life is about 5700 yr, it will decay to insignificant levels soon after it arrives (Figure 24).

Though no sorption was used in our calculations for either iodine or carbon, both elements may be slightly to significantly retarded by other processes. Carbon-14 will probably be retarded to some degree by exchange with existing carbon in carbonate minerals, principally calcite, which occur in slight amounts along the flow paths below the repository level (Spengler et al., 1981). Zeolites, which occur in abundance below the repository level, may effectively sorb iodine as indicated by research to determine how to remove iodine from the effluent streams at reprocessing plants (National Research Council, 1983, pp. 40).

No waste species with matrix retardation values greater than about 3 are projected to reach the water table within the first 100,000 yr after repository closure. Such species include all other radionuclides considered in our calculations (Table 6). Even Tc-99, with an assumed  $K_d$  of only 0.3 and a corresponding retardation value for matrix flow of about 7, would not arrive at the water table for about 210,000 yr (30,000-yr flow time multiplied by its retardation factor of 7) for the expected, upper bound on flux of 0.55 mm/yr. It follows that Tc-99 will only move about about 7 m from its emplacement

Table 7. First arrival times at the water table and travel distance from the emplacement location during the first 10,000 yr after repository closure for selected radionuclides based on a flux through the unsaturated zone of 0.5 mm/yr, 300-yr waste packages, and contact with the waste of 2.5% of the total flux.

<u>Isotope</u>	<u>Half Life (yr)</u>	<u>Arrival times at the water table (yr)</u>	<u>Travel distances for 10,000 years (m)</u>
246Cm	5.5 x 10 <sup>3</sup>	1.2 x 10 <sup>8</sup>	0.014
245Cm	9.3 x 10 <sup>3</sup>		
244Cm	1.76 x 10 <sup>1</sup>		
242Cm	4.5 x 10 <sup>-1</sup>		
243Am	7.95 x 10 <sup>3</sup>	1.2 x 10 <sup>8</sup>	0.014
242Am	1.52 x 10 <sup>2</sup>		
241Am	4.58 x 10 <sup>2</sup>		
242Pu	3.79 x 10 <sup>5</sup>	3.9 x 10 <sup>7</sup>	0.039
241Pu	1.32 x 10 <sup>1</sup>		
240Pu	6.58 x 10 <sup>3</sup>		
239Pu	2.44 x 10 <sup>4</sup>		
238Pu	8.6 x 10 <sup>1</sup>		
239Np	6.4 x 10 <sup>-3</sup>	4.2 x 10 <sup>6</sup>	0.36
237Np	2.14 x 10 <sup>6</sup>		
238U	4.51 x 10 <sup>9</sup>	1.1 x 10 <sup>6</sup>	1.35
236U	2.39 x 10 <sup>7</sup>		
235U	7.1 x 10 <sup>8</sup>		
234U	2.47 x 10 <sup>5</sup>		
233U	1.62 x 10 <sup>5</sup>		
231Pa	3.25 x 10 <sup>4</sup>	3.9 x 10 <sup>7</sup>	0.039
232Th	1.4 x 10 <sup>10</sup>	3.6 x 10 <sup>8</sup>	0.0042
230Th	8.0 x 10 <sup>4</sup>		
229Th	7.34 x 10 <sup>3</sup>		
226Ra	1.60 x 10 <sup>3</sup>	5.4 x 10 <sup>8</sup>	0.0028
225Ra	4.05 x 10 <sup>-2</sup>		
210Pb	2.23 x 10 <sup>1</sup>	3.0 x 10 <sup>6</sup>	0.5
137Cs	3.0 x 10 <sup>1</sup>	1.7 x 10 <sup>8</sup>	0.086
135Cs	3.0 x 10 <sup>6</sup>		
129I	1.59 x 10 <sup>7</sup>	3.0 x 10 <sup>4</sup>	50
126Sn	1.0 x 10 <sup>5</sup>	1.0 x 10 <sup>8</sup>	0.015
99Tc	2.15 x 10 <sup>5</sup>	2.1 x 10 <sup>5</sup>	7.14
93Zr	9.5 x 10 <sup>5</sup>	3.0 x 10 <sup>8</sup>	0.005
90Sr	2.9 x 10 <sup>1</sup>	3.3 x 10 <sup>7</sup>	0.046
59Ni	8.0 x 10 <sup>4</sup>	6.0 x 10 <sup>7</sup>	0.025
14C	5.73 x 10 <sup>3</sup>	3.0 x 10 <sup>4</sup>	50

location in the 10,000 yr during which the EPA standards apply. This assumes homogeneous flow in the unsaturated zone and a representative distance of about 300 m from the repository to the water table (Figure 11). Because Tc-99 has a half life of about 200,000 yr, enough of the initial inventory will remain when it arrives at the water table that it will contribute to the small accumulating releases.

Table 7 shows the half lives, arrival times at the water table, and travel distances for 10,000 yr for each radionuclide calculated in the same manner as for technetium. It is clear from Table 7 that the short-lived fission products responsible for most of the hazards from spent fuel during the first few hundred years after removal from the reactors, predominantly cesium and strontium, will be completely contained within the immediate vicinity of the repository until they have decayed to innocuous levels of radio-toxicity. Long-lived actinides and their short-lived daughter products, primarily radium, will be the main sources of hazards for longer time periods. Most actinides are sufficiently retarded that they will be contained near the repository for millions of years. Neptunium, with an assumed retardation of more than 140 based on a relatively low  $K_d$  of 7, will not reach the water table for more than 4 million yr. Other precursors to radium, except uranium, will be so strongly sorbed that they will not reach the water table for tens to hundreds of millions of years. By this time they will have decayed to the extent that little radium will be formed in the saturated zone. Radium is so strongly retarded (Table 6) that whatever is formed along the flow paths will be effectively retained in the unsaturated zone until it essentially decays away. Uranium, with a  $K_d$  of only 1.8, will arrive at the water table in about 1 million yr, at which time U-238 will be the only remaining uranium parent

species of significance for radium. The amount of radium in equilibrium with U-238 will remain very low because of the long-lived decay chain.

Considering that we used conservative flux and retardation values of 1 for iodine and carbon and ignored hydrodynamic dispersion and diffusion of radionuclides in the rock matrix, it is likely that even less radioactive waste than shown by Figures 22 through 24 will reach the water table at Yucca Mountain during the first 100,000 yr after repository closure. We assumed that a given percentage of the total, vertically moving flux will intercept and react with the emplaced wastes (see the three separate vertical axes on Figure 22). Additionally, we implicitly assumed that this percentage represents the cross-sectional area of the rock mass transected by vertical contaminant plumes below individual waste canisters. Dispersion and diffusion of radionuclides into the remaining portion of the rock mass would act to reduce concentrations by forming spreading contaminant plumes between the repository and the water table. These phenomena may slow the average velocity of downward radionuclide movement. Diffusion in the immediate vicinity of the waste packages will also tend to reduce solubility-limited dissolution of the waste below the rate that we estimated by assuming full saturation of the entire volume of interacting water with uranium. The amount by which dissolution rates will be slowed will depend on the relative effects of diffusion away from the waste surface and convective water flow to, along, and away from the waste surface (National Research Council, 1983, pp. 50; Kerrisk, 1984).

Because groundwater travel time is so long for low flux, the difference cumulative releases to the water table due to 300- or 1000-yr periods of containment in the waste packages would be negligible. Similarly, the additional isolation provided by transport through the saturated zone would significantly affect neither the time of initial releases nor the amount of total

releases to the accessible environment. This would be true whether saturated flow were 200 or 2000 yr or whether the accessible environment occurred 2 or 10 km from the repository. Further, the effects of radionuclide retardation will begin to affect releases only tens to hundreds of thousands of years after closure, longer than the period of required compliance with the EPA standards. Geochemical retardation will serve primarily to delay release of the actinides until they have decayed sufficiently to prevent a significant buildup of radium in the accessible environment. Though apparently not necessary for compliance with the EPA regulations, which apply only during the first 10,000 yr, geochemical retardation in the tuffs at Yucca Mountain will provide a significant barrier to longer-term waste movement between the repository level and the human environment.

In summary, it appears, for very conservative assumptions about site conditions, that a repository at Yucca Mountain will isolate nuclear waste from the human environment for tens to hundreds of thousands of years. No radioactivity from the repository will migrate even to the water table immediately beneath the repository for about 30,000 yr, far longer than the period for which compliance with the regulatory release limits must be demonstrated. Then very minor amounts of radioactive carbon and iodine may reach the water table, followed more than 100,000 yr later by small amounts of technetium. Finally, millions of years hence, long-lived actinide may begin to appear at the water table, producing minor amounts of contamination that are caused, in part, by the decay of the actinides to radium. This final source of residual contamination would be essentially negligible, however, because of the slow decay of radium parent species, mostly U-238, that survive the long transit time through the unsaturated environment at Yucca Mountain.

The results shown on Figures 22 through 24 and Table 7 represent conservative judgments about the expected performance of site conditions at Yucca Mountain. These results are used in the following subsections as a baseline for comparing performance under less likely, but possible, site conditions. The next five subsections address, in order,

1. The effects of fracture-flow (Section 4.3.2)
2. The effects of different waste-package containment periods on releases under fracture-flow conditions (Section 4.3.3)
3. The effects of different retardation mechanisms on releases under fracture-flow conditions (Section 4.3.4)
4. The influence of different definitions of the accessible environment on releases under fracture-flow conditions (Section 4.3.5)
5. The effects of a combination of nonconservative site conditions, engineered barriers, and regulatory definitions (Sections 4.3.6).

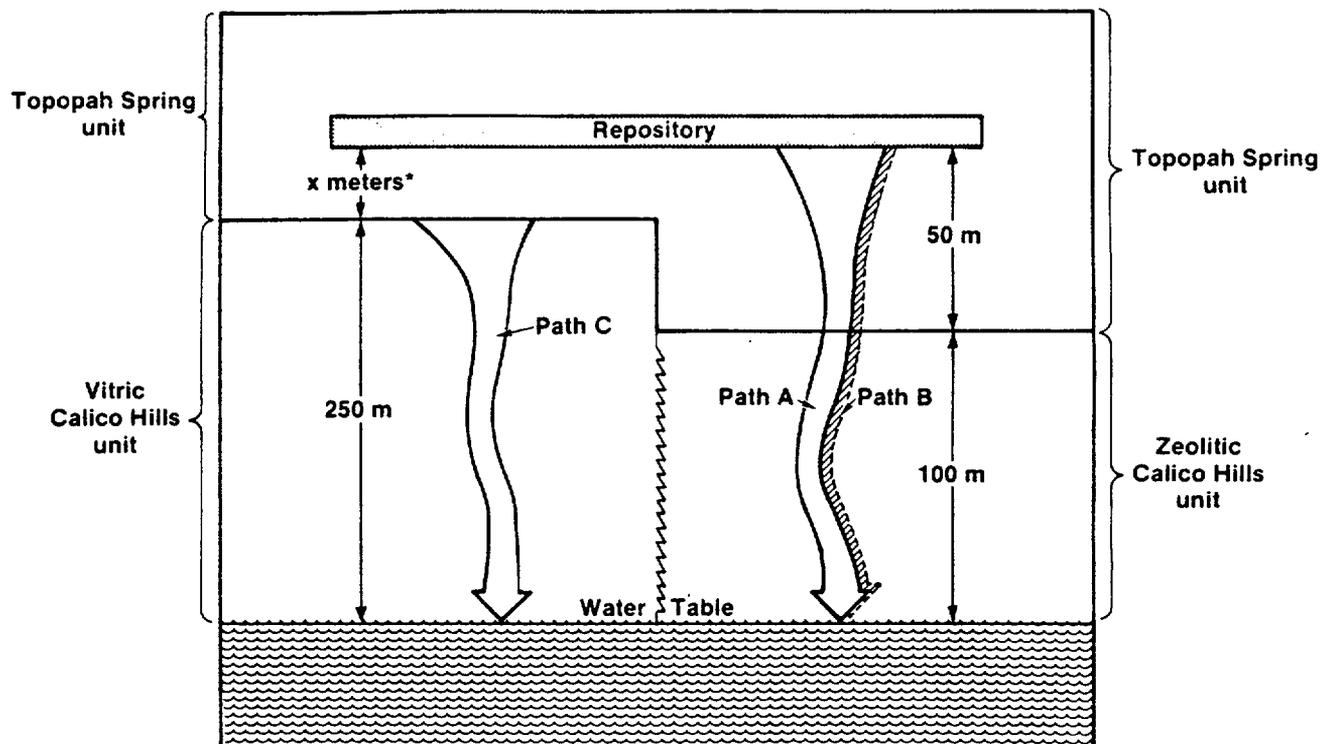
The variation of different system elements is stressed for fracture flow because for matrix flow their effects are far less significant, given the very long time before any releases could occur, as discussed above.

#### 4.3.2 Unlikely Scenarios Involving Fracture Flow

This section addresses the projected performance of a repository at Yucca Mountain under unlikely flux conditions that could cause water to flow rapidly

through fractures in the unsaturated zone. As discussed in Section 3.1.3 and analyzed in Section 4.1, a threshold of flux necessary to sustain fracture flow occurs rather sharply at a value generally corresponding to the saturated hydraulic conductivity of the rock matrix. For both the Topopah Spring and zeolitic Calico Hills units, this threshold value is about 1 mm/yr. Flux greater than this value probably will move through fractures in most portions of these two units. Because the threshold value for the vitric Calico Hills unit is nearly 1000 mm/yr, matrix flow should persist in this unit for any conceivable situations.

As a result, flux greater than 1 mm/yr would cause three types of pathways to the water table, one characterized by fracture flow and the other two by matrix flow. The three pathway types are shown schematically on Figure 25. The fracture-flow pathway (Path A) would transmit the flux in excess of 1 mm/yr through the Topopah Spring and zeolitic Calico Hills units and would occur where the zeolitic Calico Hills unit underlies the repository. For our analyses the zeolitic Calico Hills unit is assumed to underlie 60% of the total repository area, or about  $3.6 \times 10^6 \text{ m}^2$ . The first matrix-flow pathway and second overall pathway (Path B) are geometrically coincident with Path A and would transmit the flux of up to the threshold for fracture flow of about 1 mm/yr through the Topopah Spring and zeolitic Calico Hills units. We assumed a representative flow distance to the water table of 150 m for the geometrically coincident fracture and matrix flowpaths through the Topopah Spring (50 m) and zeolitic Calico Hills units (100 m). The second matrix-flow pathway and third overall path (Path C) would transmit all the flux through the portion of the repository underlain by the vitric Calico Hills unit, an area of about  $2.4 \times 10^6 \text{ m}^2$ . From the repository to the base of the Topopah Spring unit, this portion of the site would be characterized by fracture flow for



- Path A: Fracture flow for flux in excess of 1 mm/yr, identical properties assumed for Topopah Spring and Calico Hills units
- Path B: Matrix flow for flux up to 1 mm/yr
- Path C: Matrix flow for all values of flux
- \*Undefined thickness of Topopah Spring unit ignored in calculations

Figure 25. Schematic representation of three types of flow paths used for transport calculations

flux in excess of 1 mm/yr. From there to the water table, the vitric Calico Hills unit would be able to transmit all flux up to several hundred millimeters per year through the pores in the rock matrix. We conservatively ignored flow through fractures in the Topopah Spring unit for Path C and assumed a representative distance to the water table, entirely within the vitric Calico Hills unit, of 250 m (see Figure 11).

The boundary between the zeolitic (Paths A and B) and vitric (Path C) facies of the Calico Hills unit at Yucca Mountain is poorly defined. The vitric facies occurs at drill holes USW G-3 (Scott and Castellanos, 1984) and USW H-6 (J. H. Robison, USGS, personal communication), whereas the zeolitic facies occurs at the remaining drill holes in the vicinity of the site (Spengler et al., 1979, 1981; Spengler and Muller, 1984; Maldonado and Koether, 1983) (see Figure 6 for the location of drill holes relative to the repository area). Using these limited data we assumed that the vitric facies occurs in the southwestern 40% of the repository area.

Projected releases at the water table from each pathway type and for flux of 5 mm/yr are plotted on Figure 26. A flux of 5 mm/yr is used to provide a conservative basis for discussion of fracture-flow scenarios represented by the unlikely occurrence of flux in excess of 1 mm/yr. The 5 mm/yr value corresponds to a highly conservative upper limit on current flux inferred indirectly from climatic evidence as well as to a conservative value for pluvial climates, as discussed in Section 3.1.2. We adopted another conservative assumption for analysis of fracture-flow scenarios by allowing the same proportion of water flowing in fractures and in the rock matrix to contact the waste. For Figure 26, we assumed that 2.5% of the flux interacts with the waste. This amount is probably conservative even for matrix flow as discussed in Section 4.2. For fracture flow, an additional level of conservatism is

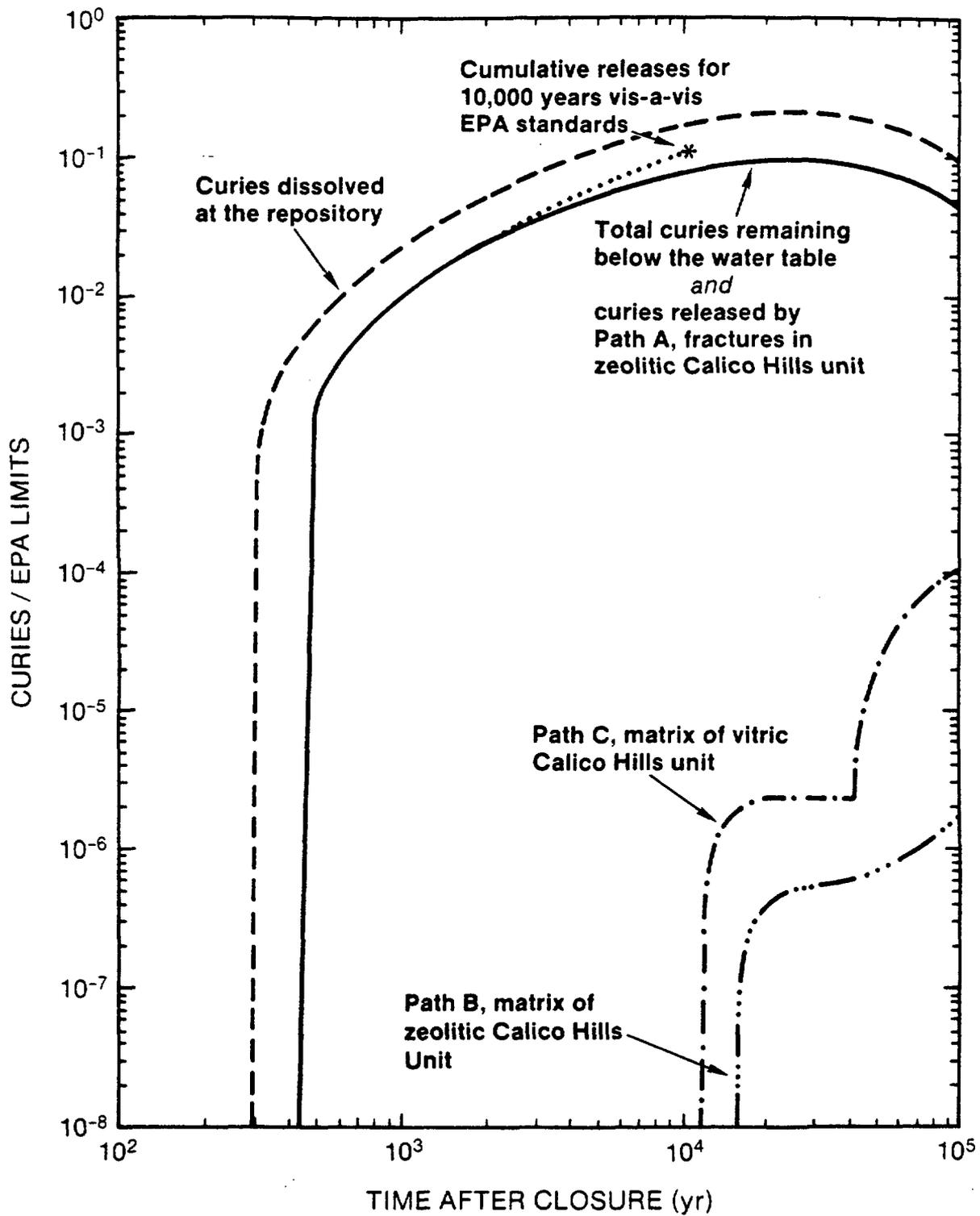


Figure 26. Ratio to the EPA limits of total curies remaining below the water table for 100,000 yr as released by three pathway types caused by a flux of 5 mm/yr (see text) and interaction of 2.5% of this flux with the wastes; 300-yr waste packages assumed; asterisk indicates cumulative releases to the water table at 10,000 yr for comparison with the EPA standard; releases at the repository shown by the upper curve.

likely, because any water in fractures would tend to rapidly drain past the emplacement holes, even if the fractures were to intercept the holes. Capillary forces would tend to resist the movement of water from the fractures into the larger voids between the waste and the rock wall of the emplacement hole, thus forcing the flow around the holes.

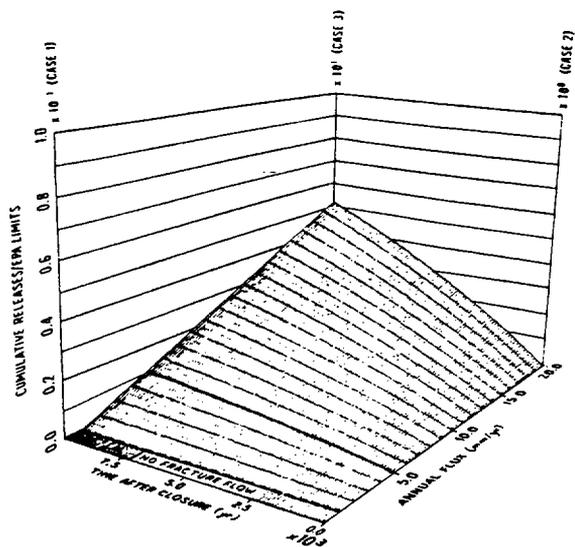
The portion of total releases resulting from transport through fracture pathways in the Topopah Spring and zeolitic Calico Hills unit is indicated by the line labeled Path A on Figure 26. Path B shows releases for the 1 mm/yr flux that continues to flow through the matrix of Topopah Spring and the zeolitic units. Releases from the matrix pathways through the vitric unit are shown by Path C. Combined releases from all three pathways are shown by the same line as Path A, indicating that releases from the fracture-flow pathways would dominate the total releases were fracture flow to occur. The upper, dotted line shows the amount of waste dissolved at the repository normalized to the EPA standards in the same manner as the lower curves. Thus, the regions between the dotted line and the lower curves represent the isolation potential provided by each of the pathways induced by fracture-flow conditions.

Figure 26 indicates that a high flux necessary to sustain fracture flow through the unsaturated zone may cause greater amounts of radioactivity to reach the water table much earlier than would the expected flux of less than 5 mm/yr represented by Figures 22 through 24. Under the reference case for fracture flow of 5 mm/yr, flow through the fractures would require only about 30 yr to reach the water table. As a result, several waste species from a repository overlying the zeolitic unit (Figure 26, Path A) would begin arriving at the water table at essentially the same time as they were released from the waste packages, assumed for Figure 26 to be 300 yr after closure. Flow

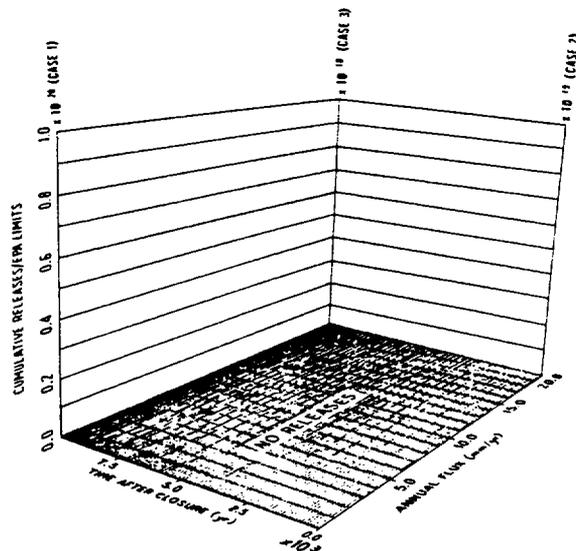
through the matrix of the Topopah Spring and zeolitic Calico Hills units (Figure 26, Path B) would be limited to a flux of 1 mm/yr and would not reach the water table for about 30,000 yr. The matrix of the vitric unit would pass all the flux up to about 1000 mm/yr, and, for a flux of 5 mm/yr, flow through this pathway would not contribute to releases at the water table until about 10,000 yr after closure (Figure 26, Path C).

Figure 27 shows the effect of increasing flux up to 20 mm/yr on releases to the water table for 10,000 yr. The reference flux for fracture flow of 5 mm/yr is accentuated on all four parts of Figure 27. An upper limit on flux of 20 mm/yr was selected as a highly conservative upper bound under pluvial conditions. Even under these extreme conditions, cumulative releases would not exceed the EPA limits unless 25% of the total flux were to become saturated with respect to uranium immediately upon contacting the waste (rear axis Figure 27D). This indicates that releases to the water table in violation of the EPA limits would require a combination of several highly unlikely conditions including an almost absurdly high flux, some mechanism for concentrating flow at the waste packages, and complete absence of delaying effects on waste dissolution provided by waste package components after the containment period.

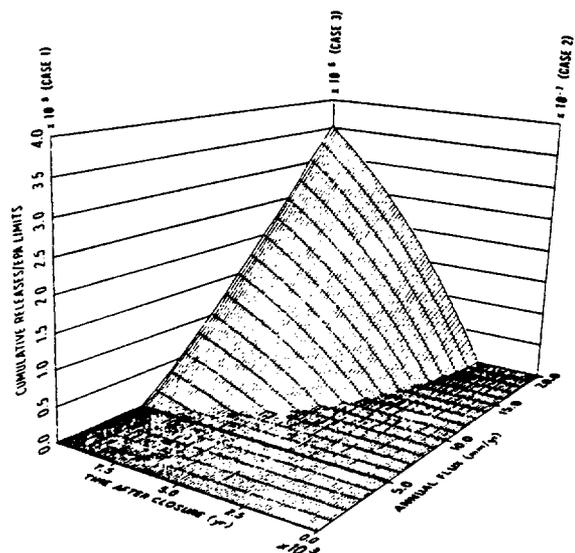
Figure 28 shows the contributions of individual radionuclides to total releases at the water table over 100,000 yr based on a 300-yr waste package, a flux of 5 mm/yr, and an assumption that 2.5% of the flux interacts with the waste. The asterisk on the figure shows the total cumulative releases to the water table for 10,000 yr for direct comparison with the EPA cumulative release limit. The dashed curve leading to the asterisk corresponds to the heavy line on Figure 27D accentuating the reference flux for fracture flow. The cumulative release curve is truncated at 10,000 yr on Figure 28 because



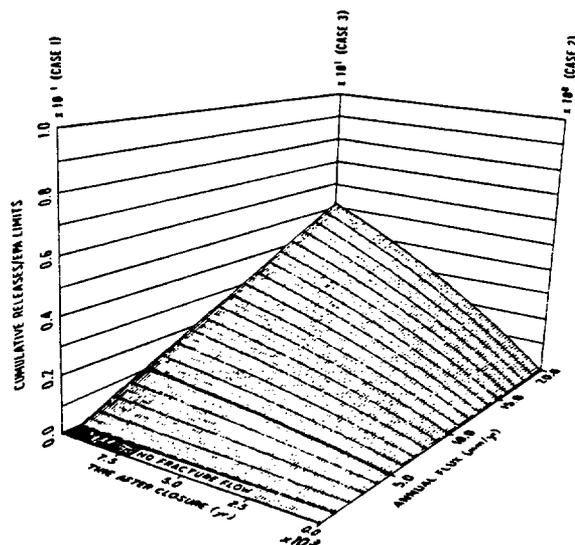
(Path A) Releases from fracture flow through zeolitic Calico Hills Unit



(Path B) Releases from matrix flow of 1 mm/yr through zeolitic Calico Hills Unit



(Path C) Releases from matrix flow through vitric Calico Hills Unit



Total releases to water table (sum of Paths A, B, and C)

Figure 27. Ratio to the EPA limits of total cumulative curies reaching the water table during 10,000 yr for flux up to 20 mm/yr; release ratios shown for three pathways caused by fracture flow conditions (Paths A, B, and C, see text) and for total releases (lower right); 300-yr waste packages assumed; heavy line accentuates reference case for fracture flow of 5 mm/yr; direct sorption was the only retardation mechanism accounted for; the three cases shown by the three vertical axes represent different amounts of the total flux contacting the waste (see text).

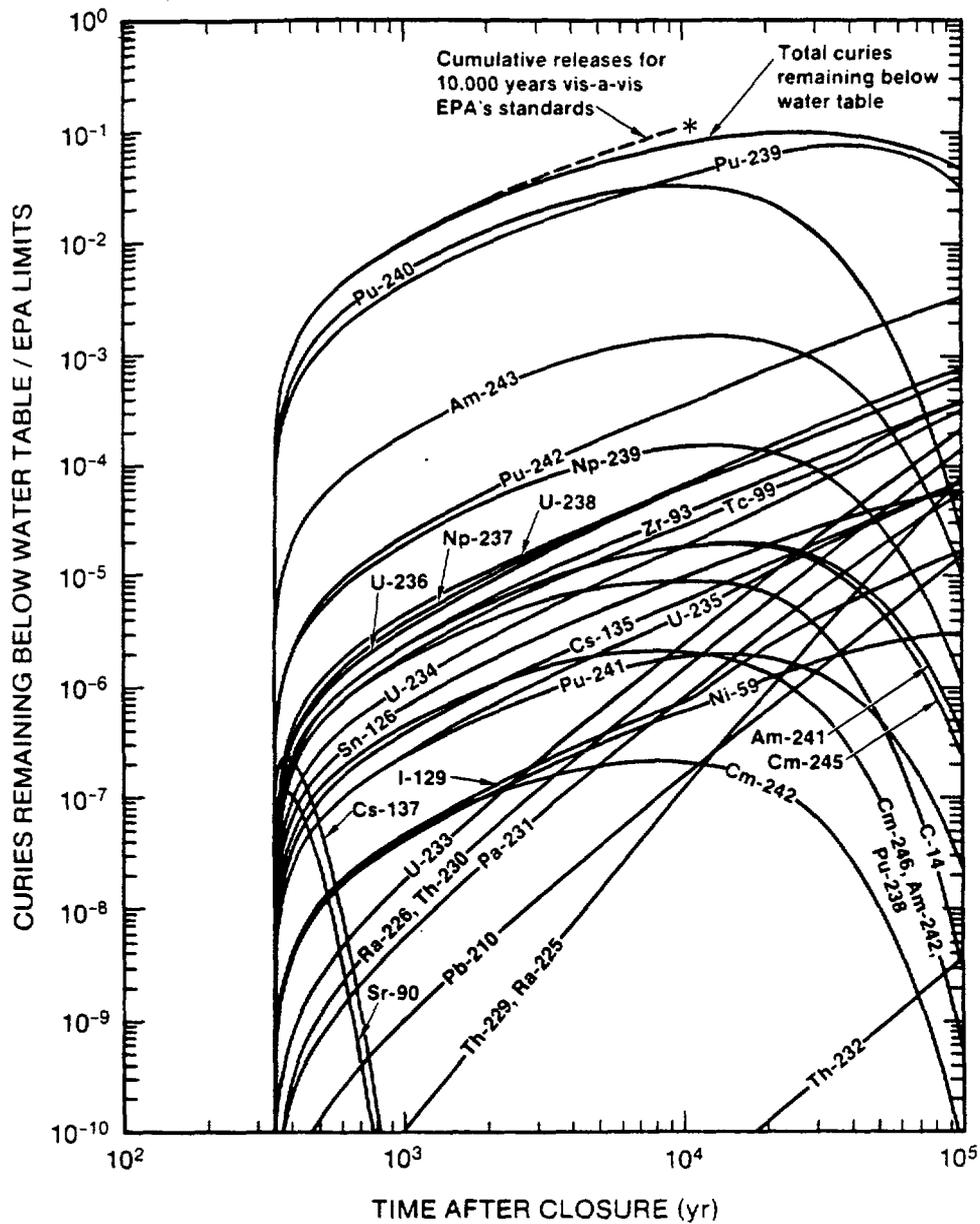


Figure 28. Ratio to the EPA limits of total curies and curies of individual radionuclides remaining below the water table for 100,000 yr for a flux of 5 mm/yr and interaction of the waste with 2.5% of this total flux; releases based on complete and instantaneous failure of all waste packages 300 yr after repository closure; asterisk indicates cumulative releases at the water table for 10,000 yr and is shown for comparison with the EPA standards; the asterisk corresponds to the end point of the line accentuating 5 mm/yr on the lower-right part of Figure 27.

this measure, vis-a-vis the EPA standards, applies only during that time period. The uppermost solid curve is noncumulative and represents the total amount of curies remaining in the saturated zone after closure. The remaining curves represent the curies of particular radionuclides remaining below the water table and show the component contributions of individual species to the total curies represented by the upper solid line.

Because the retarding effects of direct sorption along fracture surfaces are small (Table 6), early releases to the water table for fracture-flow pathways, using only sorption as a retarding mechanism, would include both fission products and actinides, total releases for about 30,000 yr would be dominated by Pu-239 and Pu-240 (Figure 28). The slight increases in C-14 and I-129 at about 12,000 yr and Tc-99 at about 40,000 yr are caused by arrival of contaminated water flowing through the matrix of the vitric Calico Hills unit.

The Tc-99 increase appears later because this element would be slightly retarded in the vitric Calico Hills unit.

Total curies in the saturated zone would continue increasing despite radionuclide decay until about 30,000 yr after repository closure, when radioactive decay, predominately of Pu-239, would finally overtake new releases (Figure 28). Because cumulative releases to the saturated zone, vis-a-vis the EPA standards, would continue to increase as an essentially straight line after 10,000 yr, Figure 28 indicates that releases calculated by methods required by the EPA for periods longer than 10,000 yr would not account for the decay of radionuclides in the accessible environment. If the short-lived fission products were isolated from the accessible environment for a few hundred years, the distinction between cumulative curies released to and curies remaining in the accessible environment would be relatively insignificant for a time period of 10,000 yr, the period over which the standards apply

(Figure 28). However, for periods of tens to hundreds of thousands of years, cumulative releases would tend to increasingly overestimate the hazards to a given population posed by the total curies remaining within the accessible environment.

Because releases by fracture flow appear to occur early and in great amounts (Figures 26 through 28), three items of importance emerge that require careful consideration before concluding that fracture flow would seriously degrade the capabilities of a repository at Yucca Mountain to isolate nuclear wastes. In particular, assumptions about waste-package performance, retardation processes along fractures, and flow and transport through the saturated zone would all become more significant if fracture flow were to occur. To illustrate the effects of each of these items on performance, the fracture-flow baseline case represented by Figures 26 through 28 will be varied independently for each of these items in the following sections.

#### 4.3.3 Effects of Waste-Package Containment on Fracture-Flow Releases

Figure 29 shows total releases at the water table caused by a flux of 5 mm/yr for 300- and 1000-yr containment periods and for a progressively failing containment period. If fracture flow occurs, a 300-yr waste package may allow curies to accumulate in the saturated zone earlier than for the case where wastes are contained in the repository for 1000 yr. Once they begin, however, the pattern of releases are almost the same for the two containment periods. By about 10,000 yr after closure, the total releases are nearly identical for 300- and 1000-yr waste packages. Thus, the difference in releases resulting from 300- and 1000-yr waste packages are not significant, even if transport times are only tens of years.

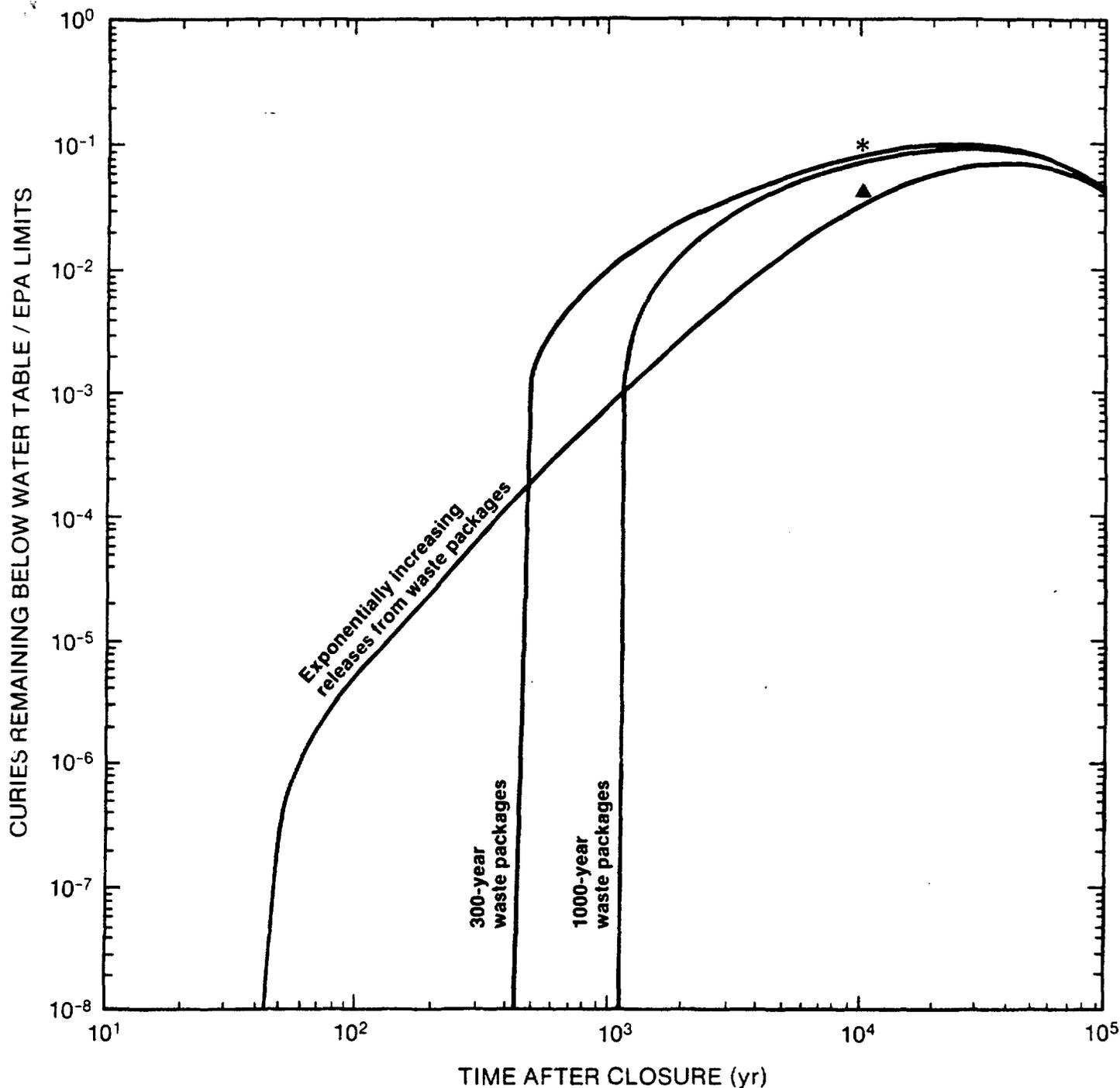


Figure 29. Comparative ratios to the EPA limits of total curies remaining below the water table for 100,000 yr based on 300- and 1000-yr waste packages and waste packages with exponentially increasing loss of containment; total flux assumed to be 5 mm/yr; interacting water assumed to be 2.5% of the total flux; asterisk shows coincident (at the scale of this graph) cumulative releases at 10,000 yr for the 300- and 1000-yr waste packages; solid triangle shows cumulative releases at 10,000 yr for the exponentially decaying waste packages.

More realistic assumptions about waste-package performance, however, do affect projected releases resulting from fracture flow (Figure 29). Releases to the water table for a flux of 5 mm/yr, assuming a mean time-to-failure for waste packages of 10,000 yr (see Section 4.2) clearly demonstrates that more realistic assumptions about waste-package failure significantly lowers releases from fracture flow to the water table for the first 10,000 yr or so. Though all radionuclides will begin to arrive earlier than for waste packages that are 100% effective for a given time, the early releases caused by progressive loss of containment will be small because of the initial limited release rate. In short, progressively decaying waste packages may allow releases to the water table to begin sooner but will limit them to levels well below those produced by waste packages that instantaneously and completely fail either 300 or 1000 yr after repository closure.

Figure 30 shows releases to the water table of individual radionuclides, assuming the progressive increase in release rates from the waste packages. This figure indicates that progressive failure would allow slight amounts of short-lived fission products and actinides, notably Cs-137, Sr-90, and Cm-244, to reach the water table. However, these contaminants would rapidly decay to innocuous levels of radioactivity. At no time would short-lived species jeopardize compliance with the EPA release limits, even if they arrived at the accessible environment 40 yr after closure of the repository (Figure 30). This is because the initial failure rates would be so low as to preclude significant releases of these or any other species.

Figures 29 and 30 are not intended as a projection of actual releases to the water table caused by an actual set of progressively failing waste packages. Their purpose is to indicate that releases to the water table by fracture flow, were it to occur, would probably be less than indicated by adopting

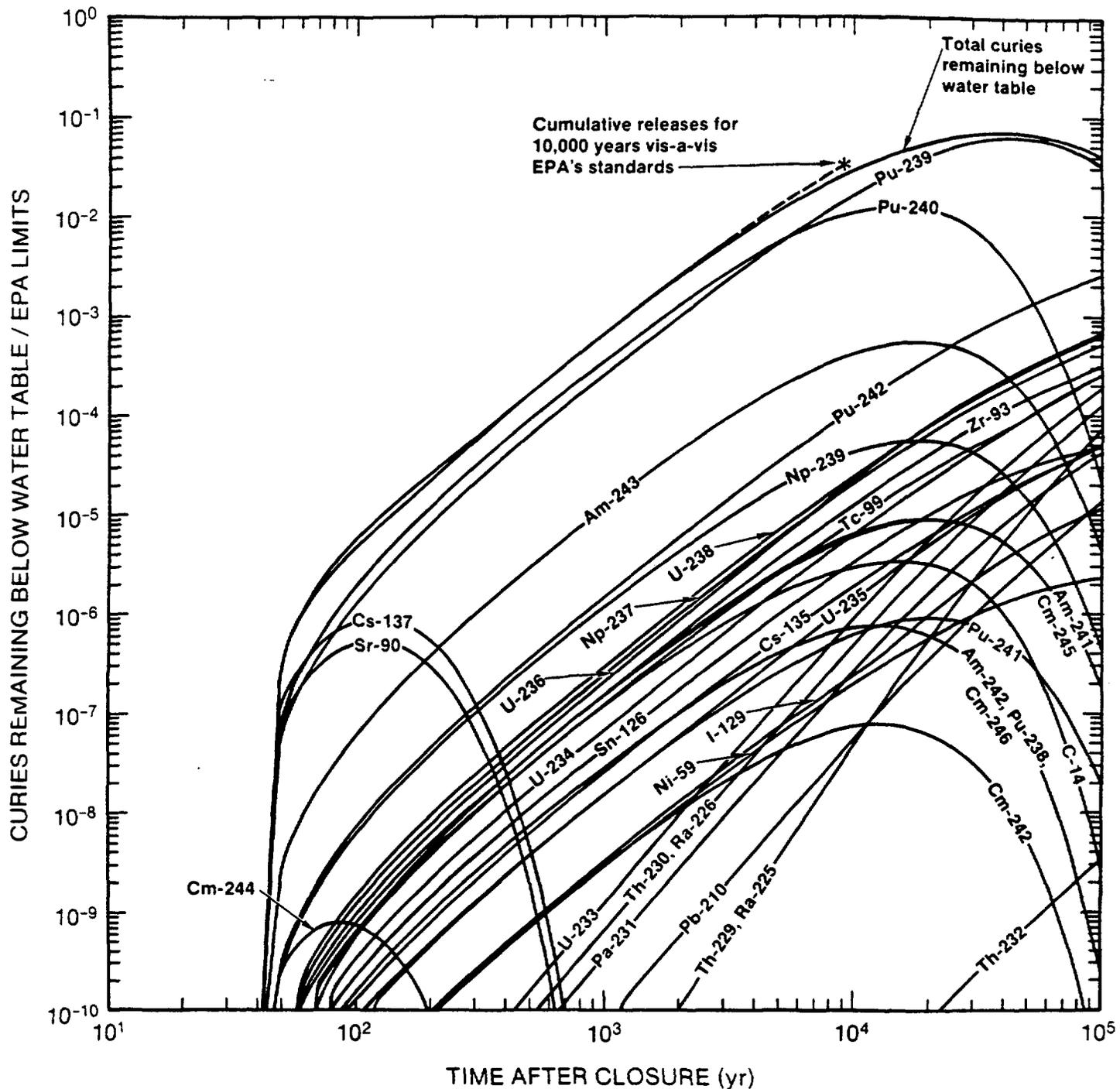


Figure 30. Ratio to the EPA limits of total curies and curies of individual radionuclides remaining below the water table for 100,000 yr based on waste packages with exponentially increasing loss of containment; total flux assumed to be 5 mm/yr; interacting water assumed to be 2.5% of the total flux; cumulative releases at 10,000 yr shown by the asterisk for comparison with the EPA standards.

an unrealistic assumption that all waste packages will fail completely and simultaneously at either 300 or 1000 yr after repository closure. The likely corrosion rate of canisters in the low flux at Yucca Mountain renders high release rates unrealistic.

#### 4.3.4 Effects of Fracture Retardation on Releases

The conservative nature of Figures 26 through 30, which are based on minimal radionuclide retardation due exclusively to sorption in fractures, is made clear by Figure 31. This figure compares releases to the water table (for unlikely, high flux conditions necessary for fracture flow) under the assumption previously used that only sorption delays radionuclide migration and two different assumptions about the effects of diffusion of radionuclides from fractures into the rock matrix. Diffusion was mentioned in Section 3.2.2 as a potentially significant mechanism for delaying radionuclide movement through fractures. Travis and others (1984) calculated a minimum effective retardation factor of about 400 caused by diffusion from fractures for a nonsorbing species, technetium, and higher values for sorbing species. On the basis of these calculations we chose a highly conservative value of 100 for retardation of all radionuclides in fractures to generate the middle curve (Curve 2) in Figure 31 and more reasonable values of 200 for nonsorbing species (C-14 and I-129), 400 for technetium, and 1000 for all other sorbing species to produce the lower curve (Curve 3). The upper curve (Curve 1) is based on retardation by sorption only and uses the values shown in Table 6 for fracture flow.

It is apparent from the Figure 31 that effective retardation due to diffusion from fractures will significantly delay releases from fracture flow to levels well within the EPA limits. In conjunction with a 300-yr waste

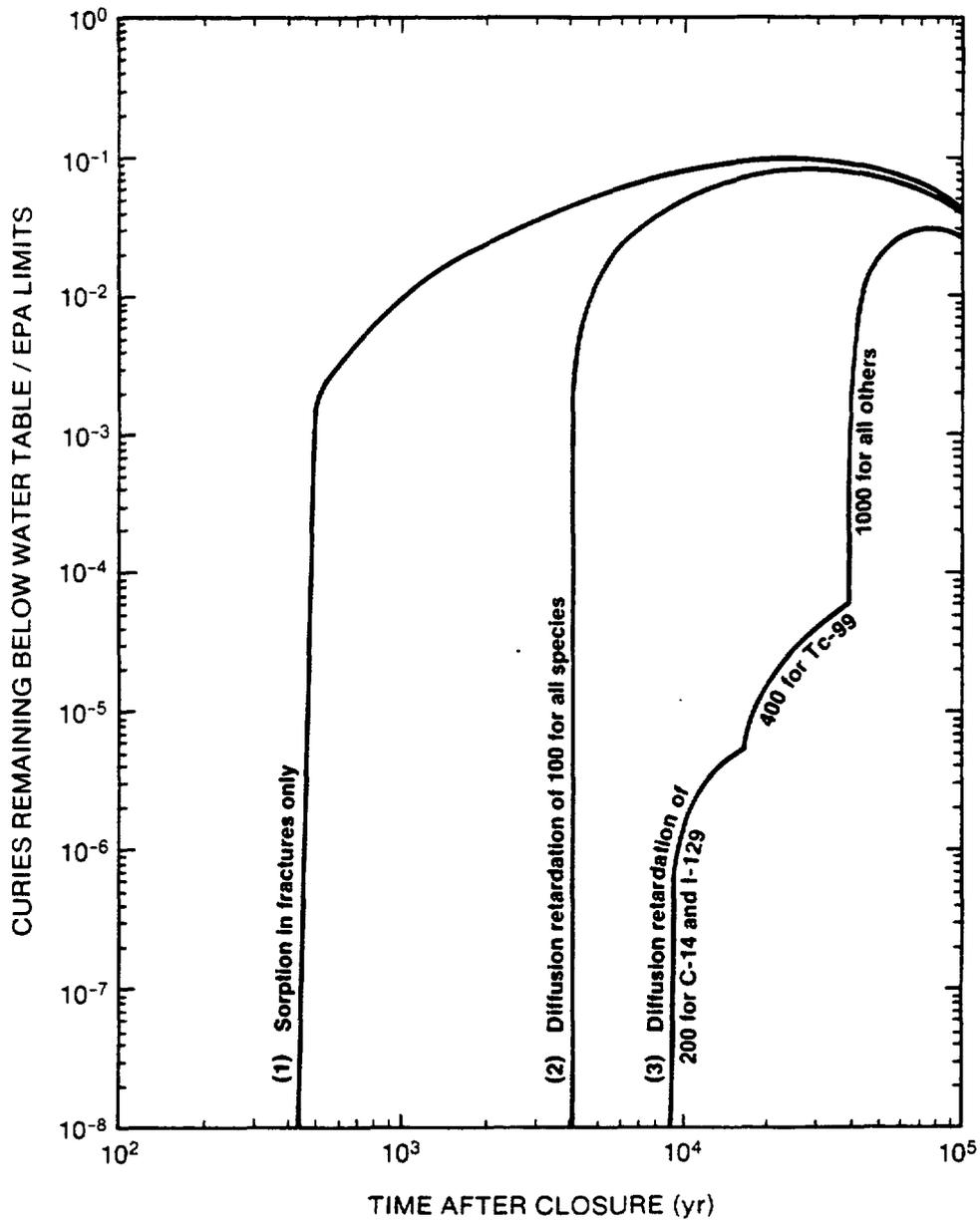


Figure 31. Comparative ratios to the EPA limits of total curies remaining below the water table for 100,000 yr based on three cases of effective retardation of radionuclides relative to fracture water flow: (1) retardation of all waste species by sorption only, (2) effective retardation of 100 by diffusion for all species, and (3) effective retardation by diffusion of 200 for nonsorbing species of C-14 and I-129, 400 for Tc-99, and 1000 for all other species; 300-yr waste packages, 5 mm/yr total flux, and interaction with 2.5% of the total flux assumed.

package (the basis for all three curves on Figure 31), realistic values for diffusion would delay initial releases to the water table from fracture flow for about 9000 years for the reference flux of 5 mm/yr. The sorbing species would arrive even later; Tc-99 at about 15,000 yr and more highly sorbing species at several decamillenia later. The purpose of Figure 31 is not to project actual releases under fracture-flow conditions, but to indicate the significant effect that radionuclide diffusion from fractures can have, were fracture flow to occur. Even in the unlikely event of significant fracture flow, releases to the water table of nonsorbing species will probably be delayed for thousands of years or longer because of the effective retardation caused by diffusion of radionuclides into and through the slowly moving water in the rock matrix. Sorbing species will probably be delayed for tens of thousands to, perhaps, millions of years, because once the wastes have diffused into the matrix, they will be retarded by sorption processes applicable to that flow regime (Travis et al., 1984).

#### 4.3.5 Effects of Saturated Flow Time on Releases to the Accessible Environment

If groundwater flows exclusively through the rock matrix in the unsaturated zone, the contribution of saturated flow time between the repository and the accessible environment would be essentially negligible, as pointed out in Section 4.3.1. However, if flux is sufficient to cause fracture flow through the unsaturated zone, then flow time in the saturated zone would probably be the dominant component of total flow time to the accessible environment, even if it were to occur only 2 km from the repository.

Figure 32 shows releases at the water table and at the end of both 200- and 2000-yr saturated flow paths; assuming 300 yr of complete containment and

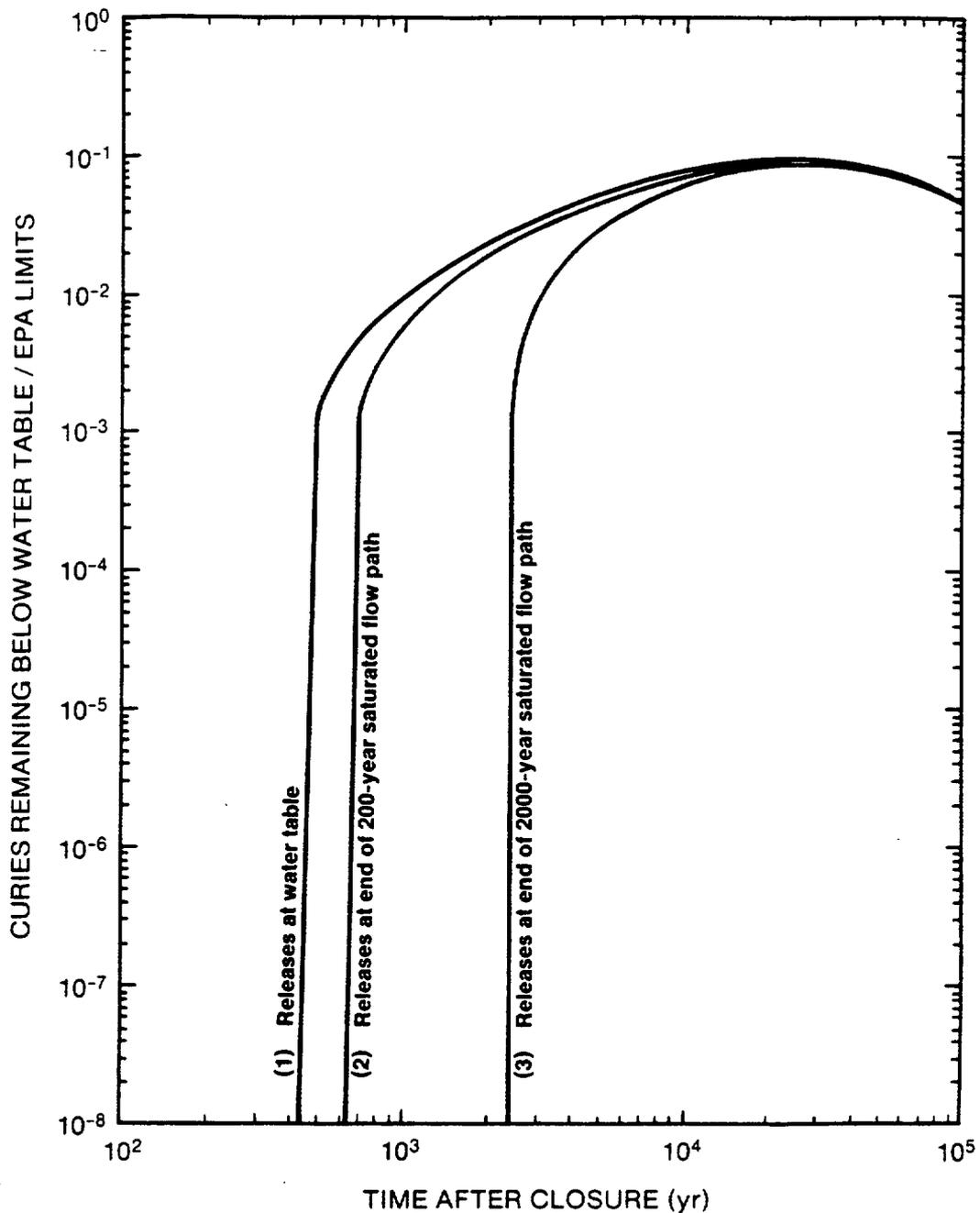


Figure 32. Comparative ratios to the EPA limits of total curies remaining below the water table for three alternative locations of the accessible environment: (1) at the water table, (2) at the end of a 200-yr saturated flow path, and (3) at the end of a 2000-yr saturated flow path; 300-yr waste packages, 5 mm/yr total flux, and interaction with 2.5% of the total flux, and retardation only by sorption assumed.

5 mm/yr flux. The two assumed flow times in the saturated zone are used to address the uncertainty associated with both the location of the accessible environment and the hydraulic properties along the saturated flow paths. Though the pattern of releases occurring at the water table, shown by the left curve in Figure 32, would not change significantly because of additional flow time through the saturated zone (middle and right curves, Figure 32), initial releases at the end of saturated flow paths would be delayed. Cumulative releases at the end of saturated flow paths would be delayed. Cumulative releases at 10,000 yr would be only slightly less than in the absence of saturated flow.

Only sorption was used as a retarding mechanism for fracture flow in both the unsaturated and the saturated zones. If effective retardation caused by diffusion from fractures were considered, as discussed in Section 4.3.4, actual releases would be much lower than indicated by Figure 32. This is because the diffusion process would be as applicable to fracture flow through the saturated zone as it is to unsaturated flow. For example, if diffusion out of fractures in the saturated zone resulted in an effective retardation of 100, then no radionuclides would arrive at the end of a 200-yr flowpath for 20,000 yr after their arrival at the water table. For these reasons, it appears that the saturated zone provides a significant, though unnecessary, barrier between the proposed repository and the accessible environment, whether that environment were to occur 2 or 10 km from the repository.

#### 4.3.6 Releases under a Combination of More Likely Site Conditions and Engineered Barriers

The previous discussion and figures of releases to the accessible environment have outlined a basis for concluding that a repository at Yucca

Mountain would be able to comply with the regulatory requirements presented in Section 1.2. The foregoing results lightly touched upon the myriad possible combinations of site conditions, engineered barriers, and regulatory definitions that affect our ability to predict the performance of a repository. The particular combinations analyzed were selected to focus attention on significant factors affecting overall performance and to establish upper bounds on possible releases under conservative assumptions about individual system components. Hitherto, the advantages of the combined effects of the several multiple barriers have not been considered. Figure 33 does so.

This figure represents a judgment about the potential magnitude and timing of releases from a repository at Yucca Mountain under a combination of nonconservative, but potentially realistic, assumptions for several system components. In this case, expected releases are based on an average flux through the unsaturated zone of 0.1 mm/yr, which is somewhat less than the 0.5 mm/yr used as a conservative reference case in Section 4.3.1. Actual flux may be essentially negligible (see Section 3.1.2), though infrequent recharge pulses probably cause some spatially restricted, short-duration flow through the unsaturated zone at Yucca Mountain. Averaged over time, this flux will not exceed, we assume, 0.1 mm/yr.

Even in the event of episodic fracture flow caused by intense recharge pulses, radionuclide retardation will probably be determined by the sorption values of the rock matrix, because diffusion will tend to drive the waste species into the matrix. Thus, radionuclide transport, if not water flow, will tend to occur within the matrix. This applies to the saturated zone as well as the unsaturated zone. So, contrary to the assumptions for Figure 32, we use retardation values of 100 for all radionuclides in the saturated zone. We assume the accessible environment will occur 2 km from the outer edge of the repository and that flow time along this distance will be 200 yr.

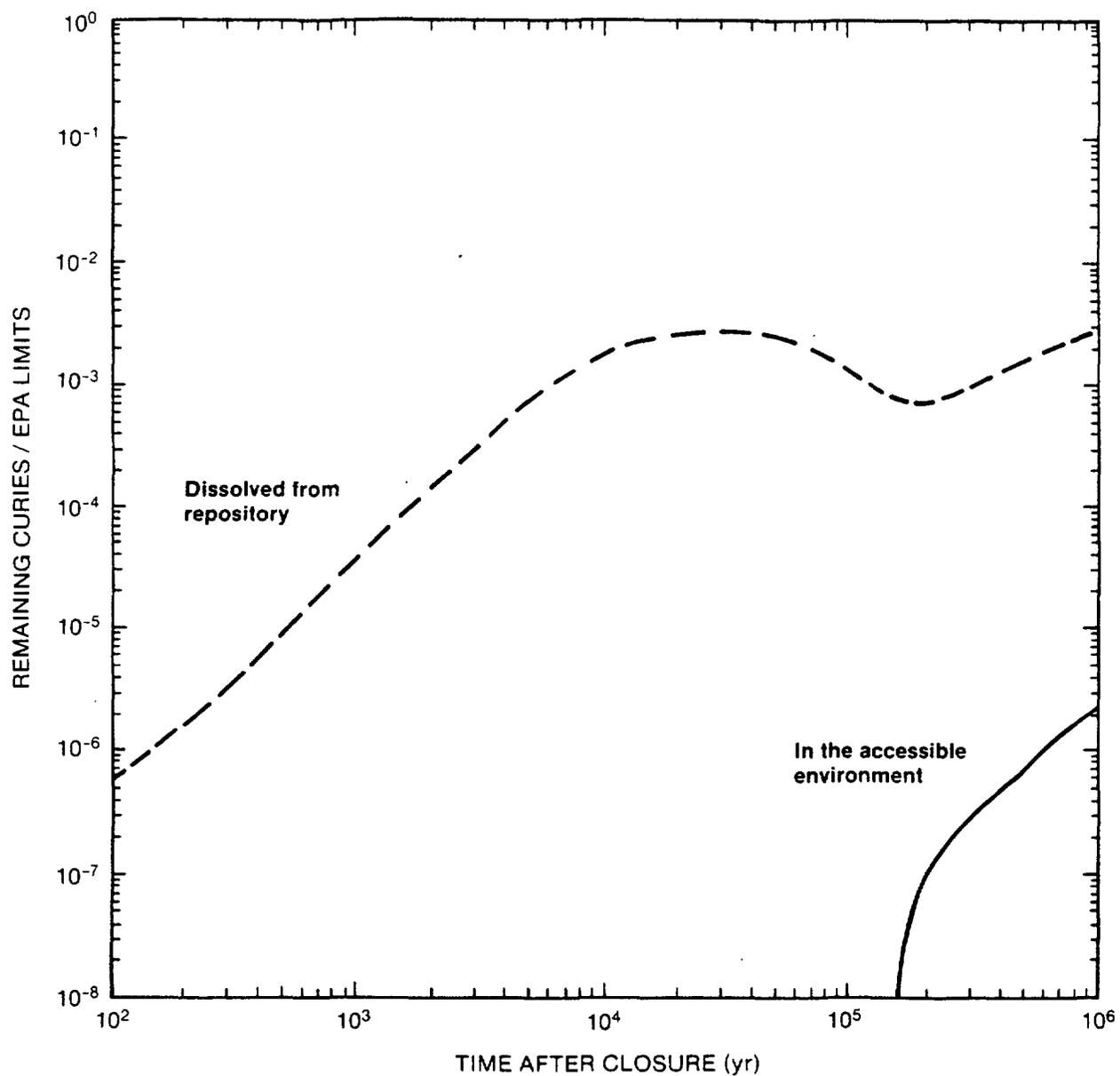


Figure 33. Ratio to the EPA limits of curies remaining in the accessible environment for 1,000,000 yr under a combination of likely barriers acting in concert at Yucca Mountain (see text); all releases shown at the accessible environment (lower curve) are I-129.

We also assume that the amount of water contacting the emplaced wastes will be much less than the total flux intercepting the area occupied by waste packages. This is because the voids in emplacement holes will most likely act as capillary barriers that effectively prevent movement of water from the rock to the waste canisters (see Section 4.2). For our calculations of releases shown in Figure 33 we used a value of 0.25% of the total flux of 0.1 mm/yr as a basis for dissolving the waste. The failure of waste packages is assumed to follow the exponential form beginning immediately after closure of the repository.

Releases to the accessible environment would be essentially negligible under the assumptions outlined above (Figure 33). Thus, for hundreds of thousands of years, available barriers acting in concert at Yucca Mountain will most likely prevent any contamination of the human environment by radioactive wastes that might be buried there.

If most barriers at Yucca Mountain perform as intended, the most likely case, then the radioactive wastes will be, in essence, permanently and completely separated from the biosphere. The assumptions on which Figure 33 is based must be confirmed by further testing of site conditions and engineering concepts. Therefore, Figure 33 is not a definitive prediction of actual repository performance. It is presented to draw attention away from the more deleterious predictions based on conservative values chosen from the range of known conditions and focus attention on plausible combinations of barriers acting in concert. Because much of this report deals with the effects of unlikely events occurring in unlikely combinations, we present Figure 33 to avoid neglect of the more likely situation represented by consideration of several barriers acting as intended.

#### 4.3.7 Summary of Releases to the Accessible Environment

The preceding sections have presented the results of calculations that show releases of radioactivity to the accessible environment under several scenarios. The individual scenarios represent plausible releases under different combinations of engineered features and site conditions.

The conditions represented by each scenario were chosen from a range of possible values for waste-package lifetimes, total flux through the unsaturated zone, the percentage of the total flux interacting with the emplaced waste (or, alternatively, the solubility of uranium), the length of flow paths to the edge of the accessible environment, and the effectiveness of diffusion in retarding radionuclide migration if fracture flow occurs. In addition, releases to the accessible environment in terms of the EPA standards were expressed in several basic ways: as cumulative releases of all radionuclides in combination, as cumulative releases of individual radionuclides, as total curies remaining in solution that were originally dissolved at the repository, as total curies remaining in solution in the accessible environment, as curies of individual radionuclides remaining in the accessible environment, and as releases to the water table from separate types of flow paths under fracture flow conditions. Releases were projected for time periods of 10,000, 100,000, and 1,000,000 yr. Finally, two other result formats were presented in tabular form, the time of arrival at the water table and the distance traveled in 10,000 yr for individual radionuclides.

Table 8 summarizes the conditions and release formats presented in each of the figures and the tables that shows results in Chapter 4. This table indicates the breadth of the parametric variations considered in this study. Because the consideration of alternative parameters was extensive, Table 8 is intended to organize and clarify for the reader our analyses of various combinations of parameters.

Table 8. Summary of conditions considered in calculating potential releases of radionuclides from a repository at Yucca Mountain.

	Figure 21	Figure 22	Figure 23	Figure 24	Figure 26	Figure 27	Figure 28	Figure 29	Figure 30	Figure 31	Figure 32	Figure 33	Table 7
<b>Waste-Package Lifetime</b>													
300 years	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
1000 years								✓	✓				
exponentially increasing loss of containment								✓	✓				✓
<b>Total Flux Through the Unsaturated Zone</b>													
0.1 mm/yr (most likely case)													✓
0.5 mm/yr (reference, upper bound case for current conditions)			✓	✓									✓
5.0 mm/yr (reference case for unlikely fracture flow, likely upper bound for pluvial conditions)					✓		✓	✓	✓	✓	✓	✓	✓
0 to 1 mm/yr (range for matrix flow)	✓	✓											
0 to 20 mm/yr (range for matrix plus fracture flow)						✓							
<b>Percentage of Flux Interacting With Waste (or) Solubility of U for Case 2</b>													
(Case 1) 0.25% (or) $4 \times 10^{-5}$ kg/m <sup>3</sup>	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
(Case 2) 2.5% (or) $4 \times 10^{-4}$ kg/m <sup>3</sup>	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
(Case 3) 25.0% (or) $4 \times 10^{-3}$ kg/m <sup>3</sup>	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
<b>Length of Flow Paths to the Accessible Environment</b>													
150 m (Topopah Spring plus zeolitic Calico Hills)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
250 m (vitrific Calico Hills)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
150 m and 250 m (see above) plus 200 years of saturated flow													✓
150 m and 250 m (see above) plus 2000 years of saturated flow													✓
300 m (overall representative distance to water table)													✓
<b>Retardation by Diffusion From Fracture Flow</b>													
0 (flux < 1 mm/yr, no fracture flow)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
0 (sorption only along fracture surfaces)													✓
100 (for all species)													✓
200 (C-14 and I-129), 400 (Tc-99), and 1000 (all other species)													✓
<b>Types of Releases Normalized to the EPA Standards</b>													
total cumulative releases to the accessible environment	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
cumulative releases of individual radionuclides to the accessible environment													✓
total remaining curies originally dissolved from the repository	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
total curies remaining in the accessible environment													✓
curies of individual radionuclides remaining in the accessible environment													✓
curies released to the accessible environment by separate flow paths													✓
<b>Time Period of Plots</b>													
10,000 Years	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
100,000 Years													✓
1,000,000 Years													✓
<b>Time Required for Individual Radionuclides to Reach the Water Table</b>													
													✓
<b>Migration Distance of Individual Radionuclides in 10,000 Years</b>													
													✓

## CHAPTER 5. CONCLUSIONS

The unsaturated zone at Yucca Mountain offers several distinct features for isolating nuclear wastes from the human environment. Paramount among these is the small amount of water available to dissolve the waste after it has been emplaced. This water is limited by the arid climate of southern Nevada, which prevents much water from seeping into the earth. The thick unsaturated zone is a result of this limited water flux. The mechanisms of water movement within the unsaturated zone are also uniquely suited to prevent or significantly slow transport of wastes from a repository. Openings in the rock, such as those created by the repository itself, will tend to block the flow of water, quite the opposite of the situation in saturated rocks. This fact lends confidence to a conclusion that little water will be able to reach the waste, and it ameliorates concerns about repository-induced or natural changes that might break, crack, or otherwise fracture the rocks around a repository. Even if the available water is able to contact and dissolve the waste, the low flux in conjunction with the high porosity of the rock matrix will probably limit flow velocities to the extent that no water will reach the water table for tens to hundreds of thousands of years.

Another distinct set of features of the Yucca Mountain site is provided by the volcanic materials from which the rocks are made. The volcanic deposits are highly porous yet, in most cases, highly impermeable. The chemical characteristics of the minerals, particularly zeolites that occur in abundance below the repository level, have strong affinities for ionic waste species, providing a highly sorptive rock mass for delaying waste migration. In combination these properties lend sponge-like properties to the rocks that will tend to draw all or most waste elements into the rock matrix and hold them there for very long times.

By assigning reasonable values to the processes and properties that describe these conditions, the calculations made for this study indicate that no wastes could move the several hundred meters from the repository level to the underlying water table in the 10,000 yr for which performance standards of the EPA will be applied. It is likely that no wastes would arrive at the water table for hundreds of thousands of years, and then only insignificant hazards would be posed by the remaining radioactive material. Under the most likely conditions, the behavior of the waste package will be relatively unimportant in assuring adequate isolation of the waste, because releases from the waste packages can only occur very slowly under the prevailing flux. Similarly, the definition of the accessible environment will have little effect on the overall releases to it, assuming the unsaturated zone is not included within the definition. Water travel time through the unsaturated zone alone is sufficient to provide the necessary isolation. If the assumptions used in this study bound the conditions at Yucca Mountain, it is likely that because of the long water-flow time, geochemical retardation at Yucca Mountain is not essential to ensure compliance with regulatory standards. Geochemical processes will, however, add considerable confidence in the ability of the site to perform satisfactorily.

There are certain unlikely combinations of conditions, each condition in itself unlikely, whereby a repository at Yucca Mountain might release wastes in amounts approaching those permitted by the EPA. High releases might occur primarily because of a peculiar situation that dictates rapid fracture flow through the unsaturated zone if flux exceeds a threshold determined by the carrying capacity of the rock matrix. At this threshold an abrupt transition between matrix and fracture flow occurs, and flow times to the water table discontinuously change from tens of thousands of years for matrix flow to tens

of years for fracture flow. However, fracture flow would not be expected to jeopardize complete isolation for 10,000 yr, because it would probably be accompanied by a process whereby wastes would diffuse from fractures into the rock matrix. If fracture flow were to somehow occur in the absence of this diffusion, the performance of waste packages and the buffering isolation provided by the saturated zone might become more significant elements in the overall performance of a repository at Yucca Mountain.

Because data and understanding about water flow and contaminant transport in deep, unsaturated fractured environments are just beginning to emerge, complete dismissal of the rapid-release scenarios is not possible at this time. Therefore, site characterization and theoretical research should focus on establishing the flux through the unsaturated zone at Yucca Mountain, including the manner in which it is temporally and spatially distributed. Such efforts require information about the spatial distribution of hydraulic conductivity as a function of moisture content, development of better understanding of the conditions that dictate the transition between fracture and matrix flow, and empirical and theoretical studies of the magnitude of the diffusion process in unsaturated, fractured media. Until the level of understanding for these items is improved, the pattern of results presented in this report must be considered provisional.

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## Appendix A

### Description of the Basis for Transport Calculations

A repository contains  $M(t)$  metric tons of heavy metal radioactive waste in a planar horizon distributed over an area expressed in square meters. The repository is assumed to be a height,  $H$ , in meters above the water table. The volume of groundwater moving vertically downward through a unit area at the repository horizon per unit time is called the flux and is assumed to be a parameter,  $F$ , given in meters per year. Flow in the unsaturated zone is assumed to obey Darcy's law. The boundary of the accessible environment is assumed to occur in the saturated zone a distance 2 to 10 km downgradient from eastern edge of repository. Water flow time through the saturated zone is treated as a constant,  $T^S$ .

#### A.1 Water Flow

Let  $j$ , a subscript, identify two components of the medium (porous matrix and fractures) with  $j=1$  denoting the matrix and  $j=2$  denoting the fractures. Darcy's law for flow in both the matrix and fractures is expressed by

$$F_j = -K_j \frac{dh_j}{dl} \quad (\text{m/yr}) \quad (1)$$

where  $h_j$  is hydraulic head,  $\frac{dh_j}{dl}$  is the hydraulic gradient,  $K_j$  is the hydraulic conductivity, and  $F_j$  is called Darcy velocity or Darcy

flux. If  $\frac{dh_j}{dl}$  is assumed to be -1, the flux through the  $j^{\text{th}}$  medium cannot exceed the maximum hydraulic conductivity of the  $j^{\text{th}}$  medium. Thus, if the flux is less than the saturated conductivity of the matrix,  $K_{j=1}^S$ , the flux is assumed to flow through the porous matrix, and the effective hydraulic conductivity and the gradient will adjust to satisfy equation (1). If the flux is greater than  $K_{j=1}^S$ , the excess flux,  $F_{j=2}$ , will flow through fractures of sufficient conductivity to satisfy equation (1).

The average particle velocity of water,  $V_j$ , is

$$V_j = \frac{F_j}{n_j} \quad (\text{m/yr}) \quad (2)$$

where  $n_j$  is the effective porosity of the  $j^{\text{th}}$  medium. The water travel time through  $H_j$  thickness of unsaturated zone in meters,  $T_j^u$ , is

$$T_j^u = \frac{H_j n_j}{F_j} \quad (\text{yr}). \quad (3)$$

Saturated flow time is treated as a constant,  $T^S$ , which was assigned a value of either 0, 200, or 2000 yr (see Section 4.1) for this report. The

total water travel time,  $T_j^W$ , from repository to accessible environment is the sum of travel time in the saturated zone,  $T^S$ , and the travel time in unsaturated zone, and is

$$T_j^W = T_j^U + T^S \quad (\text{yr}). \quad (4)$$

Assigning a value of zero to  $T^S$  thus allows a consideration of flow only to the water table.

#### A.2 Waste Dissolution

The flux that passes through the host rock may intercept the radioactive waste located at the repository. The volume of water that could possibly interact annually with waste, for either matrix or fracture flow, is the total flow through the repository area and is given by

$$Q_j = F_j \cdot A \quad (\text{m}^3/\text{yr}) \quad (5)$$

where  $Q_j$  is the annual flow rate through  $j^{\text{th}}$  medium,  $F_j$  is the annual flux through  $j^{\text{th}}$  medium, and  $A$  is the area of repository. The annual amount of water in cubic meters actually intercepting the waste emplacement area,  $q_j$ , is given by

$$q_j = F_j \cdot A \cdot \alpha_j \quad (\text{m}^3/\text{yr}) \quad (6)$$

where  $\alpha_j$  is the ratio of the area of occupied by the waste (or the effective cross-sectional area for water flow associated with the dissolving waste) to the total repository area.

The water intercepting the waste-emplacment area may not contact radioactive waste unless the canister fails. We treat canister failure in two ways: (1) a constant lifetime of either 300 or 1000 years represents the time of immediate and simultaneous failure of all canisters, i.e., having a step function at the constant life time,  $T_f$ .

$$G(t) = U(t - T_f) \quad (7)$$

where

$$U(t - T_f) = 0 \text{ if } t \leq T_f$$

$$U(t - T_f) = 1 \text{ if } t > T_f$$

(2) canister lifetime is assumed to be a variable in the sense that the lifetime distribution of the canister failure is exponential, i.e., having a probability density function of

$$g(t) = \begin{cases} \frac{1}{\mu} \exp(-t/\mu) & t \geq 0 \\ 0 & t < 0 \end{cases} \quad (8)$$

for which the cumulative distribution is

$$G(t) = \int_{-\infty}^t g(y) dy = \begin{cases} 1 - \exp(-t/\mu) & t \geq 0 \\ 0 & t < 0 \end{cases} \quad (9)$$

The parameter  $\mu$  is referred to as the mean time-to-failure of the waste canisters.

Wastes contacted by water are assumed to dissolve congruently with uranium on the mass basis. Thus, given an effective solubility limit of uranium,  $S_{i=u}$  ( $\text{kg}/\text{m}^3$ ), the expected annual dissolution rate for uranium is given by

$$D_{i=u,j}(t) = q_j \cdot S_{i=u} \cdot G(t) \quad (\text{kg}/\text{yr}). \quad (10)$$

For the  $i^{\text{th}}$  radionuclide, the annual dissolution rate is given by

$$D_{i,j}(t) = D_{i=u,j}(t) \cdot \frac{m_i(t)}{m_{i=u}(t)} \quad (\text{kg/yr}) \quad (11)$$

where  $m_i(t)$  is the inventory of  $i^{\text{th}}$  radionuclide in kilograms at time,  $t$ , and  $i=u$  represents uranium. Since radionuclides are assumed to dissolve instantaneously when they are in contact with water, the mass release rate to water is the same as the dissolution rate. The total amount of waste

released  $\sum_{i=1}^N \Delta m_i(t)$ , is simply the sum of dissolved amounts for all species.

$$\sum_{i=1}^N \Delta m_i(t) = \sum_{i=1}^N \sum_{j=1}^2 D_{i,j}(t) \quad (\text{kg}) \quad (12)$$

where  $N$  is the number of radionuclide species.

The annual fractional release rate is defined as

$$R = \frac{\sum_{i=1}^N \Delta m_i(t)}{\sum_{i=1}^N m_i(t)} \quad (\text{yr}^{-1}). \quad (13)$$

Substituting equations 11 and 12 for  $\sum_{i=1}^N \Delta m_i(t)$

$$R = \frac{\sum_{j=1}^2 D_{i=u,j}(t)}{m_{i=u}(t)} \quad (\text{yr}^{-1}) \quad (14)$$

demonstrates that congruent leaching yields an annual fractional release rate for the total waste mass equal to the release rate of uranium. Assuming  $q_j$  and  $S_{i=u}$  do not change in time and  $G(t) = 1$  (in equation 10),  $D_{i=u}(t)$  is a constant. If the  $R$  is small so that mass removal is negligible over the time period of concern,  $R$  is essentially constant because  $m_{i=u}(t)$  is dominated by U-238 with a half-life of nearly five billion years.

Given the initial inventories of radionuclides, assuming no removal, the amount of mass  $m_i(t)$ , and  $\Delta m_i(t)$  that is present at some time  $(t)$  after the initial time  $(t_0)$  can be computed analytically by solving a system of ordinary differential equations (Bateman, 1910).

The rate of annual curie releases for the  $i^{\text{th}}$  species to the water flowing through the  $j^{\text{th}}$  medium is

$$C_{i,j}(t) = a_i D_{i,j}(t) \quad (\text{curies/yr}). \quad (15)$$

To assess compliance of the annual release rate for each radionuclide with the NRC criterion (10 CFR 60.113), an "NRC Ratio" ( $NR_i$ ) is calculated as

$$NR_i = \frac{\sum_{j=1}^2 C_{i,j}(t)}{NL_i} \quad (16)$$

where  $NL_i$  is the NRC release limit for  $i^{\text{th}}$  radionuclide defined in Table

1. Similarly, a total NRC Ratio may be computed with

$$NR = \sum_{i=1}^N NR_i \quad (17)$$

### A.3 Radionuclide Transport

The transport time for the  $i^{\text{th}}$  radionuclide,  $T_{i,j}^r$ , is related to the water travel time by

$$T_{i,j}^r = Rd_{i,j} T_j^w \quad (\text{yr}) \quad (18)$$

where  $Rd_{i,j}$  is a dimensionless retardation factor for  $i^{th}$  species through  $j^{th}$  medium. In porous medium flow, i.e.,  $j=1$ , the retardation factor is defined as

$$Rd_{i,1} = 1 + \frac{\gamma Kd_i}{n_1} \quad (19)$$

where the  $\gamma$  is the bulk rock density in  $kg/m^3$ ,  $Kd_i$  in  $m^3/kg$  is the distribution coefficient or sorption ratio for the  $i^{th}$  radionuclide in porous matrix blocks, and  $n_1$  is the effective porosity of the blocks.

In the case of water flow through fractures, i.e.  $j=2$ , it is more appropriate, as suggested by Burkholder (1976), to relate the retardation factor to a distribution coefficient  $Ka_i$  by the equation

$$Rd_{i,2} = 1 + Rf \cdot Ka_i \quad (20)$$

where  $Rf$  is the ratio of surface area to void space (volume) for the fracture opening through which the nuclide is being transported. The  $Ka_i$  value is a measure of moles of  $i^{th}$  nuclide in the sorbed state per unit surface area divided by the moles of  $i^{th}$  nuclide in the dissolved state per unit volume

of groundwater when the groundwater and medium are in equilibrium. Since the fracture surface is irregular, the actual surface area with which the nuclide reacts is unknown. A simple practical approach is to express  $Ka_1$  relative to the area of an assumed planar fracture surface (Freeze and Cherry, 1979, p. 410). In this case, the retardation factors for fracture flow become

$$Rd_{i,2} = 1 + \frac{2Ka_i}{b} \quad (21)$$

where  $b$  is the aperture width of the fracture.

The differential equations describing the transport of radionuclides and their decay products through geologic media with sorption are listed below.

$$\begin{aligned} Rd_1 \frac{\partial C_1}{\partial t} + v \frac{\partial C_1}{\partial z} &= -Rd_1 \lambda_1 C_1 \\ Rd_2 \frac{\partial C_2}{\partial t} + v \frac{\partial C_2}{\partial z} &= -Rd_2 \lambda_2 C_2 + Rd_1 \lambda_1 C_1 \\ Rd_3 \frac{\partial C_3}{\partial t} + v \frac{\partial C_3}{\partial z} &= -Rd_3 \lambda_3 C_3 + Rd_2 \lambda_2 C_2 \\ &\vdots \\ Rd_l \frac{\partial C_l}{\partial t} + v \frac{\partial C_l}{\partial z} &= -Rd_l \lambda_l C_l + Rd_{l-1} \lambda_{l-1} C_{l-1} \end{aligned} \quad (22)$$

where

- $C_l$  = nuclide concentration for the  $l^{\text{th}}$  member of decay chain,  
Ci/m<sup>3</sup>
- $Rd_l$  = retardation factor for the  $l^{\text{th}}$  member of decay chain
- $\lambda_l$  = decay constant for the  $l^{\text{th}}$  member of decay chain, 1/yr
- $v$  = groundwater velocity, m/yr.

The phenomena of hydrodynamic dispersion and diffusion are not considered in this equation.

#### A.4 Release to the Accessible Environment

The rate of release of radionuclides from the repository to the accessible environment may be expressed in curies as  $C_{i,j}^a$ , which is the curie release rate from the repository to the unsaturated zone (Equation 15) delayed by the transport time (Equation 18) and reduced by radioactive decay during the transport time.

The computation of  $C_{i,j}^a$  is accomplished by a direct-simulation approach that defines numerical structures that represent the material balances of the  $l^{\text{th}}$  members of decay chains and all preceding chain members (Equation 22) over a differential length of flow path and a differential time. The annual release rate of curies from the repository,  $C_{i,j}(t)$ , is represented during

transport as a set of discrete lumped slugs. Each slug by definition is of zero size but with spatial coordinates,  $(Z_p)_{i,j}$ , and a discrete quantity of curies,  $(C_p)_{i,j}$ , where  $p$  is the slug index,  $p = 1, 2, \dots, N_p$ , and  $N_p$  is the number of slugs for the  $i^{\text{th}}$  radionuclide in the  $j^{\text{th}}$  path.

During a given time step, a new location for each slug is computed from the characteristics of convective mechanisms

$$\frac{d(Z_p)_{i,j}}{dt} = \frac{V}{Rd_{i,j}} \quad (23)$$

where

$V$  = water velocity along the flow path in the  $z$  direction.

The new location of the release parcel at  $k + 1$  time step is calculated by

$$(Z_p^{k+1})_{i,j} = (Z_p^k)_{i,j} + \Delta t_k \frac{V}{Rd_{i,j}} \quad (24)$$

where

$\Delta t_k$  = the time increment for  $k^{\text{th}}$  time step

$(Z_p^k)_{i,j}$  = the  $z$  location of the slug  $p$  at the  $k^{\text{th}}$  time step

$(Z_p^{k+1})_{i,j}$  = the  $z$  location of the slug  $p$  at the  $(k + 1)^{\text{th}}$  time step.

The slugs in the flow path and the source term at the repository are adjusted for radioactive decay in each time step by solving the Bateman equations. A five-member chain of equations is used in computation of radionuclide quantities as a function of time. For the decay chains with very rapidly decaying nuclides, each of the short-lived nuclides, i.e., Pu-241, Ra-225, Am-241, Cm-242, Pb-210, and Np-239, is assumed to remain in secular equilibrium with its immediate precursor. No branching ratios are considered in the decay chains.

The rate of release of radionuclides to the accessible environment,  $C_i^a$ , is simply the sum of slugs transported across the boundary to the accessible environment per unit time.

Cumulative curies released to the accessible environment for the  $i^{\text{th}}$  radionuclide,  $\bar{C}_i^a$ , are numerically approximated by integrating the curie release rates.

$$\bar{C}_i^a(t) = \sum_{j=1}^2 \sum_{k=1}^K C_{i,j}^a(t) \Delta t_k \quad (\text{curies}) \quad (25)$$

where  $k$  is the index for time steps,  $K$  is the number of time steps, and  $\Delta t_k$  is the time increment. The performance of the repository is measured by comparing cumulative curies released to accessible environment with the EPA release limits (40 CFR 191). The measure of performance is simply the "EPA release ratio" (ER),

$$ER = \sum_{i=1}^N \frac{\bar{C}_i^a(t)}{EL_i} \quad (26)$$

where  $EL_i$  is the EPA limit for  $i^{\text{th}}$  radionuclide defined in Table 1.

## Appendix B

Listing of Computer Program Used for Calculations

```

PROGRAM SAMPLE
DIMENSION RTCUR(3,100,5,14),RTCURS(3,100,5,3),RATIO(5,14),
*DEF(100),SRC(100),DISCI(100),FRM(100)
DIMENSION PT(11,102),TFAC(100),YR(100),PT1(100),PT2(100),
*PT3(100),PT4(100),PT5(100),PT6(100),IPAK(70)
DIMENSION REC(20),TT(3,20),VS(3,20),FL(3,20,3)
*,DR(3,20,3),TL(3,20,3),FR(3,20,3)
*,TTC(20),TTB(20),RECM(20),TTM(20)
DIMENSION AL(5,14),NEC(14),CONI(5,14),CONN(5,14),HLS(5,3),
*ALS(5,3),SPA(5,14),AM(5,14),RNA(5,3),RCH(8,14),CONIS(5,3),
*HL(5,14),CUM(5,14),AMS(5,3),RCI(5,14),RCIS(5,3)
DIMENSION ALP(5,3),CURS(5,3),CUMS(5,3),PAR(5,3),NECS(3),
*CUR(5,14),SPAS(5,3),PAC(5,3)
DIMENSION RL(5,14),RLS(5,3),CIR(5,14),CIRS(5,3)
DIMENSION CITOT(4,20,100),AERAT(4,20,100),AETOT(4,20,100)
DIMENSION CITOT2(4,20,100),CIRAT(4,20,100),AECID(4,20,100),
*RC(100,5,14)
DIMENSION DIS(3,100,5,14),AGIN(100,5,14),RDF(3,5,14),
*RDFS(3,5,3),AGINS(100,5,3),RCS(100,5,3),
*SUR(4,100,5,14),SURS(4,100,5,3),SUC(4,100,5,14),SUCS(4,100,5,3)
DIMENSION TM21(14),TM31(14),TM41(14),TM51(14),TM32(14),TM42(14),
*TM52(14),TM53(14),TM54(14),TM43(14),CONIW(5,14),CONNW(5,14),
*DCON(5,14)
DIMENSION EP(3),FRA(3),FRF(3),DI(3),FLUX(3,20),NP(20)
DATA(EP(I),I=1,3)/0.2,0.1,0.001/
DATA(FRF(I),I=1,3)/0.4,0.6,0.6/
DATA(FRA(I),I=1,3)/0.25,0.025,0.0025/
DATA(DI(I),I=1,3)/250.,150.,150./
DATA(RCH(1,I),I=1,3)/"C-14","TC-99","I-129"/
DATA(RCH(I,4),I=1,4)/"CM-244","PU-240","U-236","TH-232"/
DATA(RCH(I,5),I=1,4)/"CM-245","NP-237",
*"U-233","TH-229"/
DATA(RCH(I,6),I=1,5)/"CM-246","PU-242",
*"U-238","U-234","TH-230"/
DATA(RCH(I,7),I=1,4)/"AM-243","PU-239","U-235","PA-231"/
DATA(RCH(1,I),I=8,13)/"NI-59","CS-135","SN-126","ZR-93",
*"SR-90","CS-137"/
DATA(AM(1,I),I=1,3)/14.,99.,129./
DATA(AM(I,4),I=1,4)/244.,240.,236.,232./
DATA(AM(I,5),I=1,4)/245.,          237.,233.,229./
DATA(AM(I,6),I=1,5)/246.,          242.,          238.,234.,230./
DATA(AM(I,7),I=1,4)/243.,239.,235.,231./
DATA(AM(1,I),I=8,13)/59.,135.,126.,93.,90.,137./
DATA(HL(1,J),J=1,3)/5.73E3,2.15E5,1.59E7/
DATA(HL(I,4),I=1,4)/17.6,6.58E3,2.39E7,1.4E10/
DATA(HL(I,5),I=1,4)/9.3E3,          2.44E6,1.62E5,7.34E4/
DATA(HL(I,6),I=1,5)/5.5E3,          3.79E5,          4.51E9,

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*2.47E5,8.4E4/
DATA(HL(I,7),I=1,4)/7.95E3,2.44E4,7.1E8,3.25E4/
DATA(HL(1,I),I=8,13)/8.E4,3.E6,1.E5,9.5E5,29.,30./
DATA(NEC(I),I=1,14)/1,1,1,4,4,5,4,1,1,1,1,1,1,1/
DATA(RNA(I,1),I=1,3)/"PU - 241","AM - 241","RA-225"/
DATA(RNA(I,2),I=1,5)/"AM-242","CM-242","PU-238","RA-226",
*"PB-210"/
DATA RNA(1,3)/"NP-239"/
DATA(ALS(I,1),I=1,3)/5.25E-2,1.51E-3,17.11/
DATA(ALS(I,2),I=1,5)/4.56E-3,1.54,8.06E-3,4.33E-4,3.11E-2/
DATA ALS(1,3)/108.28/
DATA(NECS(I),I=1,3)/3,5,1/
DATA(SPAS(I,1),I=1,3)/1.12E2,3.24,3.92E4/
DATA(SPAS(I,2),I=1,5)/9.72,3.32E3,17.5,.988,76.3/
DATA SPAS(1,3)/2.33E5/
DATA(RL(1,I),I=1,3)/7.0E3,7.0E5,7.0E4/
DATA(RL(J,4),J=1,4)/7.E4,7.0E3,7000.,7000./
DATA(RL(J,5),J=1,4)/7000.,7000.,7000.,7000./
DATA(RL(J,6),J=1,5)/7000.,7000.,7000.,7000.,7000./
DATA(RL(J,7),J=1,4)/7000.,7000.,7000.,7000./
DATA(RL(1,I),I=8,13)/7.E4,7.E4,7.E4,7.E4,7.E4,7.E4/
DATA(RLS(I,1),I=1,3)/7.E4,7000.,7000./
DATA(RLS(I,2),I=1,5)/7000.,7.E4,7000.,7000.,7.E4/
DATA RLS(1,3)/7.E4/
DATA(RDF(1,1,I),I=1,3)/1.,4.,1./
DATA(RDF(1,I,4),I=1,4)/1800.,640.,19.,5800./
DATA(RDF(1,I,5),I=1,4)/1800.,71.,19.,5800./
DATA(RDF(1,I,6),I=1,5)/1800.,640.,19.,19.,5800./
DATA(RDF(1,I,7),I=1,4)/1800.,640.,19.,640./
DATA(RDF(1,1,I),I=8,13)/1000.,2900.,1700.,5000.,530.,2900./
DATA(RDFS(1,I,1),I=1,3)/640.,1800.,9000./
DATA(RDFS(1,I,2),I=1,5)/1800.,1800.,640.,9000.,51./
DATA RDFS(1,1,3)/71./
DATA(RDF(2,1,I),I=1,3)/1.,7.,1./
DATA(RDF(2,I,4),I=1,4)/3600.,1300.,37.,12000./
DATA(RDF(2,I,5),I=1,4)/3600.,140.,37.,12000./
DATA(RDF(2,I,6),I=1,5)/3600.,1300.,37.,37.,12000./
DATA(RDF(2,I,7),I=1,4)/3600.,1300.,37.,1300./
DATA(RDF(2,1,I),I=8,13)/2000.,5800.,3400.,10000.,1100.,5800./
DATA(RDFS(2,I,1),I=1,3)/1300.,3600.,18000./
DATA(RDFS(2,I,2),I=1,5)/3600.,3600.,1300.,18000.,100./
DATA RDFS(2,1,3)/140./
DATA(RDF(3,1,I),I=1,3)/1.,1.,1./
DATA(RDF(3,I,4),I=1,4)/1.,1.,1.,1.1/
DATA(RDF(3,I,5),I=1,4)/1.,1.0,1.0,1.1/
DATA(RDF(3,I,6),I=1,5)/1.,1.,1.0,1.0,1.1/
DATA(RDF(3,I,7),I=1,4)/1.,1.,1.0,1./
DATA(RDF(3,1,I),I=8,13)/1.,1.,1.,1.1,1.,1./

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DATA(RDFS(3,I,1),I=1,3)/1.,1.,1.2/
DATA(RDFS(3,I,2),I=1,5)/1.,1.,1.,1.2,1.0/
DATA RDFS(3,1,3)/1.0/
DATA(TFAC(I),I=1,100)/100*1000./
CCC
DOE-28-10
DATA(CONI(1,I),I=1,3)/2.2E3,5.35E7,1.33E7/
DATA(CONI(I,4),I=1,4)/7.57E5,1.39E8,2.43E8,70./
DATA(CONI(I,5),I=1,4)/8.03E4,3.08E7,2.8E2,9.2E-3/
DATA(CONI(I,6),I=1,5)/9.28E3,2.87E7,6.73E10,8.38E5,1.48E1/
DATA(CONI(I,7),I=1,4)/5.30E6,3.31E8,5.23E8,8.23/
DATA(CONI(1,I),I=8,13)/2.77E4,2.14E7,1.18E6,2.95E7,2.65E7,
*6.03E7/
DATA(CONIS(I,1),I=1,3)/4.3E7,3.47E7,1.45E-7/
DATA(CONIS(I,2),I=1,5)/7.20E4,1.79E2,8.0E6,5.24E-4,6.42E-5/
DATA CONIS(1,3)/8.23/
CCC
DOE-28-1000
C DATA(CONI(1,I),I=1,3)/1.89E3,5.35E7,1.33E7/
C DATA(CONI(I,4),I=1,4)/1.E-99,1.27E8,2.65E8,0.7/
C DATA(CONI(I,5),I=1,4)/7.58E4,9.43E7,2.22E4,3.94E-1/
C DATA(CONI(I,6),I=1,5)/7.95E3,2.87E7,6.73E10,9.06E6,2.16E4/
C DATA(CONI(I,7),I=1,4)/4.9E6,3.20E8,5.56E8,5.43E2/
C DATA(CONI(1,I),I=8,13)/2.77E4,2.14E7,1.18E6,2.95E7,6.64E-4,
C *6.7E-3/
C DATA(CONIS(I,1),I=1,3)/1.06E2,1.79E7,1.89E-3/
C DATA(CONIS(I,2),I=1,5)/7.92E2,1.96,4.4E3,70.85,0.92/
C DATA CONIS(1,3)/3.91/
NCHNS =13
IPRINT=1
IRATE=0
NL=3
C IV=3
C IV=1
IV=2
C1=1.13E13
C2=3.1558E7
C3=.693147
C5=1.
SL=4.E-4
UI=6.7967E7
AR=6.07E6
DO 2 I=1,NCHNS
N=NEC(I)
DO 2 J=1,N
AL(J,I)=C3/HL(J,I)
C4=HL(J,I)*C2
SPA(J,I)=C1/(C4*AM(J,I))
CONI(J,I)=CONI(J,I)*C5*.001
2 CONTINUE

```

```

NF=10
NT=100
TOT=0.
DO 18 I=1,NT
TOT=TOT+TFAC(I)
18 YR(I)=TOT
DO 22 I=1,NF
REC(I)=I*0.0005
FLUX(1,I)=REC(I)
IF(REC(I).LE.1.E-3)GO TO 20
FLUX(2,I)=0.001
GO TO 21
20 FLUX(2,I)=REC(I)
NP(I)=2
21 FLUX(3,I)=REC(I)-FLUX(2,I)
IF(FLUX(3,I).GT.0.) NP(I)=3
19 NL=NP(I)
DO 22 L=1,NL
VS(L,I)=FLUX(L,I)/EP(L)
C TT(L,I)=DI(L)/VS(L,I)+2000.
TL(L,I)=DI(L)/VS(L,I)
DO 22 IC=1,3
FL(L,I,IC)=AR*FLUX(L,I)*FRA(IC)*FRF(L)
DR(L,I,IC)=FL(L,I,IC)*SL
FR(L,I,IC)=DR(L,I,IC)/UI
TL(L,I,IC)=UI/DR(L,I,IC)
22 CONTINUE
DO 24 L=1,3
PRINT 100
DO 24 I=1,NF
PRINT 101,REC(I),FLUX(L,I),VS(L,I),TT(L,I),FL(L,I,1)
*,FL(L,I,2),FL(L,I,3)
24 FLUX(L,I)=1000.*FLUX(L,I)
DO 4 I=1,NCHNS
N = NEC(I)
IF(N.EQ.1)GO TO 3
TM21(I)=1./(AL(2,I)-AL(1,I))
IF(N.EQ.2)GO TO 3
TM31(I)=1./(AL(3,I)-AL(1,I))
TM32(I)=1./(AL(3,I)-AL(2,I))
IF(N.EQ.3)GO TO 3
TM41(I)=1./(AL(4,I)-AL(1,I))
TM42(I)=1./(AL(4,I)-AL(2,I))
TM43(I)=1./(AL(4,I)-AL(3,I))
IF(N.EQ.4)GO TO 3
TM51(I)=1./(AL(5,I)-AL(1,I))
TM52(I)=1./(AL(5,I)-AL(2,I))
TM53(I)=1./(AL(5,I)-AL(3,I))

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      TM54(I)=1./(AL(5,I)-AL(4,I))
3     CONTINUE
4     CONTINUE
      ALP(1,1)=AL(1,5)/ALS(1,1)
      ALP(2,1)=AL(1,5)/ALS(2,1)
      ALP(3,1)=AL(4,5)/ALS(3,1)
      ALP(1,2)=AL(1,6)/ALS(1,2)
      ALP(2,2)=AL(1,6)/ALS(2,2)
      ALP(3,2)=AL(1,6)/ALS(3,2)
      ALP(4,2)=AL(5,6)/ALS(4,2)
      ALP(5,2)=AL(5,6)/ALS(5,2)
      ALP(1,3)=AL(1,7)/ALS(1,3)
      IF(IV.LE.3)DTT=1050.
      CALL BAT(NCHNS,AL,DTT,NEC,CONI, TM21, TM31, TM41, TM32, TM42, TM43,
*TM51, TM52, TM53, TM54, DCON)
      DO 197 I=1, NCHNS
      N=NEC(I)
      DO 197 J=1, N
197  RCI(J,I)=DCON(J,I)
      IF(IV.EQ.1) DTT=50.
      IF(IV.EQ.2) DTT=350.
      IF(IV.EQ.3) DTT=1050.
      CALL BAT(NCHNS,AL,DTT,NEC,CONI, TM21, TM31, TM41, TM32, TM42, TM43,
*TM51, TM52, TM53, TM54, DCON)
      TOTCI=0.
      DO 167 I=1, NCHNS
      N=NEC(I)
      DO 167 J=1, N
      RCI(J,I)=DCON(J,I)*SPA(J,I)*1000.*1.E-5
C     PRINT 104, I, J, RCI(J,I)
C 104  FORMAT (1X,2I10,1PE10.2)
167  TOTCI=TOTCI+RCI(J,I)
      PAR(1,1)=DCON(1,5)
      PAR(2,1)=DCON(1,5)
      PAR(3,1)=DCON(4,5)
      PAR(1,2)=DCON(1,6)
      PAR(2,2)=DCON(1,6)
      PAR(3,2)=DCON(1,6)
      PAR(4,2)=DCON(5,6)
      PAR(5,2)=DCON(5,6)
      PAR(1,3)=DCON(1,7)
      DO 168 MI=1,3
      MN=NECS(MI)
      DO 168 MJ=1,MN
      RCIS(MJ,MI)=PAR(MJ,MI)*ALP(MJ,MI)*SPAS(MJ,MI)*1000.*1.E-5
C     PRINT 104, MJ, MI, RCIS(MJ,MI)
168  TOTCI=TOTCI+RCIS(MJ,MI)
      TOTCI=TOTCI/1000.

```

```

C      PRINT 105,TOTCI
C 105 FORMAT (1X,3(1PE10.2,1X))
      IF (IV.EQ.1) DTT=50.
      IF (IV.EQ.2) DTT=350.
      IF (IV.EQ.3) DTT=1050.
      CALL BAT(NCHNS,AL,DTT,NEC,CONI, TM21, TM31, TM41, TM32, TM42, TM43,
*TM51, TM52, TM53, TM54, DCON)
      DO 198 I=1,NCHNS
      N=NEC(I)
      DO 198 J=1,N
      IF (RCI(J,I).LT.TOTCI) RCI(J,I)=TOTCI
C      RDF(3,J,I)=100.
198 CONI(J,I)=DCON(J,I)
      PAR(1,1)=DCON(1,5)
      PAR(2,1)=DCON(1,5)
      PAR(3,1)=DCON(4,5)
      PAR(1,2)=DCON(1,6)
      PAR(2,2)=DCON(1,6)
      PAR(3,2)=DCON(1,6)
      PAR(4,2)=DCON(5,6)
      PAR(5,2)=DCON(5,6)
      PAR(1,3)=DCON(1,7)
      DO 196 MI=1,3
      MN=NECS(MI)
      DO 196 MJ=1,MN
      IF (RCIS(MJ,MI).LT.TOTCI) RCIS(MJ,MI)=TOTCI
C      RDFS(3,MJ,MI)=100.
196 CONIS(MJ,MI)=PAR(MJ,MI)*ALP(MJ,MI)
C      DO 5000 IC=1,3
      IC=2
      T=0.
      DO 203 K=1,NT
      DISCI(K)=0.
203 SRC(K)=0.
      DO 202 K=1,NT
      T=T+TFAC(K)
      CALL BAT(NCHNS,AL,T,NEC,CONI, TM21, TM31, TM41, TM32, TM42, TM43,
*TM51, TM52, TM53, TM54, CONN)
C      DEF(K)=1.-EXP(-T/10000.)
      DEF(K)=1.
      FRM(K)=SL*AR*0.0005*0.025*DEF(K)/UI
      DO 200 I=1,NCHNS
      N=NEC(I)
      DO 200 J=1,N
      AGIN(K,J,I)=CONN(J,I)
      RC(K,J,I)=AGIN(K,J,I)*SPA(J,I)*1000.*FRM(K)/RCI(J,I)
      DISCI(K)=DISCI(K)+AGIN(K,J,I)*SPA(J,I)*1000.*FRM(K)
      SRC(K)=SRC(K)+RC(K,J,I)

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```

200  CONTINUE
    PAC(1,1)=CONN(1,5)
    PAC(2,1)=CONN(1,5)
    PAC(3,1)=CONN(4,5)
    PAC(1,2)=CONN(1,6)
    PAC(2,2)=CONN(1,6)
    PAC(3,2)=CONN(1,6)
    PAC(4,2)=CONN(5,6)
    PAC(5,2)=CONN(5,6)
    PAC(1,3)=CONN(1,7)
    DO 201 MI=1,3
    MN=NECS(MI)
    DO 201 MJ=1,MN
    AGINS(K,MJ,MI)=PAC(MJ,MI)*ALP(MJ,MI)
    RCS(K,MJ,MI)=AGINS(K,MJ,MI)*SPAS(MJ,MI)*1000.*FRM(K)/RCIS(MJ,MI)
    DISCI(K)=DISCI(K)+AGINS(K,MJ,MI)*SPAS(MJ,MI)*1000.*FRM(K)
201  SRC(K)=SRC(K)+RCS(K,MJ,MI)
202  CONTINUE
    DO 500 M=1,NF
    PRINT 308,REC(M)
    NL=NP(M)
    DO 211 L=1,NL
    T=0.
    DO 211 KA=1,NT
    CIRAT(L,M,KA)=0.
    CITOT(L,M,KA)=0.
    T=T+TFAC(KA)
    DO 212 IB=1,3
    NA=NECS(IB)
    DO 212 JB=1,NA
    SUCS(L,KA,JB,IB)=0.
212  SURS(L,KA,JB,IB)=0.
    DO 211 IA=1,NCHNS
    NA=NEC(IA)
    DO 211 JA=1,NA
    DIS(L,KA,JA,IA)=DR(L,M,IC)*AGIN(KA,JA,IA)*DEF(KA)*1000./UI
    RTCUR(L,KA,JA,IA)=0.
    SUC(L,KA,JA,IA)=0.
211  SUR(L,KA,JA,IA)=0.
    DO 250 L=1,NL
    T=0.
    DO 250 K=1,NT
    T=T+TFAC(K)
    DO 210 IB=1,NCHNS
    NB=NEC(IB)
    DO 210 JB=1,NB
    CONIW(JB,IB)=DIS(L,K,JB,IB)
    IF(K.EQ.1)CONNW(JB,IB)=0.

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210 CONTINUE
    DT=TFAC(K)
    CALL BAT(NCHNS,AL,DT,NEC,CONIW,TM21,TM31,TM41,TM32,TM42,TM43,
*TM51,TM52,TM53,TM54,DCON)
    DO 216 IB =1,NCHNS
        NB=NEC(IB)
        DO 216 JB=1,NB
            IF (CONIW(JB,IB).LT.1.E-999)GO TO 216
            RATIO(JB,IB)=DCON(JB,IB)/CONIW(JB,IB)
216 CONTINUE
            IF(M.EQ.1.AND.IC.EQ.2.AND.L.EQ.1)GO TO 218
            GO TO 219
218 PRINT 302,T
            PRINT 320
            PRINT 309
219 CONTINUE
            SCIRAT=0.
            SCITOT=0.
            DO 220 IB =1,NCHNS
                NB=NEC(IB)
                DO 220 JB=1,NB
                    CONNW(JB,IB)=CONNW(JB,IB)*RATIO(JB,IB)+DCON(JB,IB)*DT
                    CUR(JB,IB)=SPA(JB,IB)*CONNW(JB,IB)
                    RTCUR(L,K,JB,IB)=DCON(JB,IB)*SPA(JB,IB)
                    SCITOT=SCITOT+CUR(JB,IB)
                    CIR(JB,IB)=CUR(JB,IB)/RL(JB,IB)
                    SCIRAT=SCIRAT+CIR(JB,IB)
                    CUM(JB,IB)=CONNW(JB,IB)
220 CONTINUE
                PAR(1,1)=CONNW(1,5)
                PAR(2,1)=CONNW(1,5)
                PAR(3,1)=CONNW(4,5)
                PAR(1,2)=CONNW(1,6)
                PAR(2,2)=CONNW(1,6)
                PAR(3,2)=CONNW(1,6)
                PAR(4,2)=CONNW(5,6)
                PAR(5,2)=CONNW(5,6)
                PAR(1,3)=CONNW(1,7)
                PAC(1,1)=DCON(1,5)
                PAC(2,1)=DCON(1,5)
                PAC(3,1)=DCON(4,5)
                PAC(1,2)=DCON(1,6)
                PAC(2,2)=DCON(1,6)
                PAC(3,2)=DCON(1,6)
                PAC(4,2)=DCON(5,6)
                PAC(5,2)=DCON(5,6)
                PAC(1,3)=DCON(1,7)
                DO 260 MI=1,3

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MN=NECS(MI)
DO 260 MJ=1,MN
CUMS(MJ,MI)=PAR(MJ,MI)*ALP(MJ,MI)
CURS(MJ,MI)=CUMS(MJ,MI)*SPAS(MJ,MI)
CIRS(MJ,MI)=CURS(MJ,MI)/RLS(MJ,MI)
266 RTCURS(L,K,MJ,MI)=PAC(MJ,MI)*ALP(MJ,MI)*SPAS(MJ,MI)
SCIRAT=SCIRAT+CIRS(MJ,MI)
SCITOT=SCITOT+CURS(MJ,MI)
260 CONTINUE
CIRAT(L,M,K)=SCIRAT
CITOT(L,M,K)=SCITOT
CITOT2(L,M,K)=ALOG10(SCITOT)
NCHNS6=NCHNS-6
DO 240 IB=1,NCHNS6
NB=NEC(IB)
DO 240 JB=1,NB
IF(M.EQ.1.AND.IC.EQ.2.AND.L.EQ.1)GO TO 223
GO TO 224
223 CONTINUE
IF(IB.EQ.2.OR.IB.EQ.3)GO TO 221
IF(JB.NE.1)GO TO 221
IF(IB.EQ.1.OR.IB.EQ.8)GO TO 340
IF(IB.EQ.4)GO TO 341
IF(IB.EQ.5)GO TO 342
IF(IB.EQ.6)GO TO 343
IF(IB.EQ.7)GO TO 344
340 PRINT 321
PRINT 315
GO TO 221
341 PRINT 321
PRINT 311
GO TO 221
342 PRINT 321
PRINT 312
GO TO 221
343 PRINT 321
PRINT 313
GO TO 221
344 PRINT 321
PRINT 314
221 CONTINUE
PRINT 310,RCH(JB,IB),DIS(L,K,JB,IB),CUR(JB,IB),CUM(JB,IB),
*AGIN(K,JB,IB),CIR(JB,IB),RC(K,JB,IB),RTCUR(L,K,JB,IB)
IF(IB.NE.3)GO TO 230
DO 231 I7=8,13
231 PRINT 310,RCH(JB,I7),DIS(L,K,JB,I7),CUR(JB,I7),CUM(JB,I7),
*AGIN(K,JB,I7),CIR(JB,I7),RC(K,JB,I7),RTCUR(L,K,JB,I7)
230 CONTINUE

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IF (IB.EQ.5) GO TO 5
IF (IB.EQ.6) GO TO 6
IF (IB.EQ.7) GO TO 7
GO TO 224
5 GO TO (8,224,224,9)JB
8 PRINT 317,RNA(1,1),CURS(1,1),CUMS(1,1),AGINS(K,1,1),CIRS(1,1),
*RCS(K,1,1),RTCURS(L,K,1,1)
PRINT 317,RNA(2,1),CURS(2,1),CUMS(2,1),AGINS(K,2,1),CIRS(2,1),
*RCS(K,2,1),RTCURS(L,K,2,1)
GO TO 224
9 PRINT 317,RNA(3,1),CURS(3,1),CUMS(3,1),AGINS(K,3,1),CIRS(3,1),
*RCS(K,3,1),RTCURS(L,K,3,1)
GO TO 224
6 GO TO (11,12,224,224,13)JB
11 PRINT 317,RNA(1,2),CURS(1,2),CUMS(1,2),AGINS(K,1,2),CIRS(1,2),
*RCS(K,1,2),RTCURS(L,K,1,2)
PRINT 317,RNA(2,2),CURS(2,2),CUMS(2,2),AGINS(K,2,2),CIRS(2,2),
*RCS(K,2,2),RTCURS(L,K,2,2)
GO TO 224
12 PRINT 317,RNA(3,2),CURS(3,2),CUMS(3,2),AGINS(K,3,2),CIRS(3,2),
*RCS(K,3,2),RTCURS(L,K,3,2)
GO TO 224
13 PRINT 317,RNA(4,2),CURS(4,2),CUMS(4,2),AGINS(K,4,2),CIRS(4,2),
*RCS(K,4,2),RTCURS(L,K,4,2)
PRINT 317,RNA(5,2),CURS(5,2),CUMS(5,2),AGINS(K,5,2),CIRS(5,2),
*RCS(K,5,2),RTCURS(L,K,5,2)
GO TO 224
7 GO TO (14,224,224,224)JB
14 PRINT 317,RNA(1,3),CURS(1,3),CUMS(1,3),AGINS(K,1,3),CIRS(1,3),
*RCS(K,1,3),RTCURS(L,K,1,3)
224 CONTINUE
240 CONTINUE
250 CONTINUE
DO 290 L=1,NL
T=0.
DO 280 K=1,NT
T=T+TFAC(K)
DO 270 IB =1,NCHNS
NB=NEC(IB)
DO 270 JB=1,NB
RT=TT(L,M)*RDF(L,JB,IB)
RTT=TOT-RT
IF (RTT.LT.0..OR.T.GT.RTT)GO TO 270
KRT=0
TRT=T+RT
DO 278 KT=1,NT
IF (TRT.LT.0.)GO TO 279
TRT=TRT-TFAC(KT)

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278 KRT=KRT+1
279 CONTINUE
    SUR(L,KRT,JB,IB)=SUR(L,KRT,JB,IB)
    *+RTCUR(L,KRT,JB,IB)*DEF(K)/DEF(KRT)*TFAC(K)
270 CONTINUE
    DO 280 MI=1,3
    MN=NECS(MI)
    DO 280 MJ=1,MN
    RTS=TT(L,M)*RDFS(L,MJ,MI)
    RTTS=TOT-RTS
    IF(RTTS.LT.0..OR.T.GT.RTTS)GO TO 280
    KRTS=0
    TRTS=T+RTS
    DO 288 KT=1,NT
    IF (TRTS.LT.0.) GO TO 289
    TRTS=TRTS-TFAC(KT)
288 KRTS=KRTS+1
289 CONTINUE
    SURS(L,KRTS,MJ,MI)=SURS(L,KRTS,MJ,MI)
    *+RTCURS(L,KRTS,MJ,MI)*DEF(K)/DEF(KRTS)*TFAC(K)
280 CONTINUE
290 CONTINUE
    DO 460 K=1,NT
    DO 493 IA=1,NCHNS
    NA=NEC(IA)
    DO 493 JA=1,NA
493 SUR(4,K,JA,IA)=SUR(1,K,JA,IA)+SUR(2,K,JA,IA)+SUR(3,K,JA,IA)
    DO 494 IB=1,3
    NB=NECS(IB)
    DO 494 JB=1,NB
494 SURS(4,K,JB,IB)=SURS(1,K,JB,IB)+SURS(2,K,JB,IB)+SURS(3,K,JB,IB)
460 CONTINUE
    DO 296 L=1,NL
    DO 291 IA=1,NCHNS
    NA=NEC(IA)
    DO 291 JA=1,NA
    STOT=0.
    STOTC=0.
    DO 291 K=1,NT
    STOT=STOT+SUR(L,K,JA,IA)/RL(JA,IA)
    IF (K.EQ.1.OR.STOT.EQ.0.)GO TO 297
    STOTC=STOTC*RTCUR(L,K,JA,IA)/RTCUR(L,K-1,JA,IA)
    **DEF(K-1)/DEF(K)+SUR(L,K,JA,IA)
    */RL(JA,IA)
297 CONTINUE
    SUR(L,K,JA,IA)=STOT
    SUC(L,K,JA,IA)=STOTC
291 CONTINUE

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DO 292 IB=1,3
NB=NECS(IB)
DO 292 JB=1,NB
IF (IB.NE.1) GO TO 281
MB=5
IF (JB.EQ.1.OR.JB.EQ.2) MA=1
IF (JB.EQ.3) MA=4
GO TO 283
281 IF (IB.NE.2) GO TO 282
MB=6
IF (JB.EQ.1.OR.JB.EQ.2.OR.JB.EQ.3) MA=1
IF (JB.EQ.4.OR.JB.EQ.5) MA=5
GO TO 283
282 IF (IB.EQ.3) MB=7
IF (JB.EQ.1) MA=1
283 CONTINUE
STOTS=0.
STOTCS=0.
DO 292 K=1,NT
STOTS=STOTS+SURS(L,K,JB,IB)/RLS(JB,IB)
IF (K.EQ.1.OR.STOTS.EQ.0.) GO TO 298
STOTCS=STOTCS*RTCURS(L,K,JB,IB)/RTCURS(L,K-1,JB,IB)
**DEF(K-1)/DEF(K)
**+SURS(L,K,JB,IB)/RLS(JB,IB)
298 CONTINUE
SURS(L,K,JB,IB)=STOTS
SUCS(L,K,JB,IB)=STOTCS
292 CONTINUE
DO 295 K=1,NT
SAECID=0.
SAETOT=0.
SAERAT=0.
DO 293 IA=1,NCHNS
NA=NEC(IA)
DO 293 JA=1,NA
SAECID=SAECID+SUC(L,K,JA,IA)
SAETOT=SAETOT+SUR(L,K,JA,IA)*RL(JA,IA)
293 SAERAT=SAERAT+SUR(L,K,JA,IA)
DO 294 IB=1,3
NB=NECS(IB)
DO 294 JB=1,NB
SAECID=SAECID+SUCS(L,K,JB,IB)
SAETOT=SAETOT+SURS(L,K,JB,IB)*RLS(JB,IB)
294 SAERAT=SAERAT+SURS(L,K,JB,IB)
AECID(L,M,K)=SAECID
AETOT(L,M,K)=SAETOT
AERAT(L,M,K)=SAERAT
295 CONTINUE

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296 CONTINUE
DO 360 K=1,NT
DO 393 IA=1,NCHNS
NA=NEC(IA)
DO 393 JA=1,NA
SUR(4,K,JA,IA)=SUR(1,K,JA,IA)+SUR(2,K,JA,IA)+SUR(3,K,JA,IA)
393 SUC(4,K,JA,IA)=SUC(1,K,JA,IA)+SUC(2,K,JA,IA)+SUC(3,K,JA,IA)
DO 394 IB=1,3
NB=NECS(IB)
DO 394 JB=1,NB
SURS(4,K,JB,IB)=SURS(1,K,JB,IB)+SURS(2,K,JB,IB)+SURS(3,K,JB,IB)
394 SUCS(4,K,JB,IB)=SUCS(1,K,JB,IB)+SUCS(2,K,JB,IB)+SUCS(3,K,JB,IB)
CIRAT(4,M,K)=CIRAT(1,M,K)+CIRAT(2,M,K)+CIRAT(3,M,K)
CITOT(4,M,K)=CITOT(1,M,K)+CITOT(2,M,K)+CITOT(3,M,K)
AETOT(4,M,K)=AETOT(1,M,K)+AETOT(2,M,K)+AETOT(3,M,K)
AERAT(4,M,K)=AERAT(1,M,K)+AERAT(2,M,K)+AERAT(3,M,K)
AECID(4,M,K)=AECID(1,M,K)+AECID(2,M,K)+AECID(3,M,K)
360 CONTINUE
DO 366 L=1,NL
IF (IC.NE.2) GO TO 351
IF (IPRINT.NE.1) GO TO 350
PRINT 103,L
PRINT 322
DO 330 K=1,NT
PRINT 323,YR(K),CITOT(L,M,K),CIRAT(L,M,K),AETOT(L,M,K),
*AERAT(L,M,K),SUR(L,K,1,1),SUR(L,K,1,2),
* SUR(L,K,1,3),SUR(L,K,1,8),SUR(L,K,1,9),SUR(L,K,1,10)
330 CONTINUE
PRINT 326
DO 331 K=1,NT
PRINT 323,YR(K),SUR(L,K,1,11),SUR(L,K,1,12),SUR(L,K,1,13),
* SUR(L,K,1,4),SUR(L,K,2,4),SUR(L,K,3,4),SUR(L,K,4,4),
* SUR(L,K,1,5),SURS(L,K,1,1),SURS(L,K,2,1)
331 CONTINUE
PRINT 327
DO 332 K=1,NT
PRINT 323,YR(K),SUR(L,K,2,5),SUR(L,K,3,5),SUR(L,K,4,5),
* SURS(L,K,3,1),SUR(L,K,1,6),SURS(L,K,1,2),SUR(L,K,2,2),
* SUR(L,K,2,6),SURS(L,K,3,2),SUR(L,K,3,6)
332 CONTINUE
PRINT 328
DO 333 K=1,NT
PRINT 323,YR(K),SUR(L,K,4,6),SUR(L,K,5,6),SURS(L,K,4,2),
* SURS(L,K,5,2),SUR(L,K,1,7),SURS(L,K,1,3),SUR(L,K,2,7),
* SUR(L,K,3,7),SUR(L,K,4,7),AECID(L,M,K)
333 CONTINUE
350 CONTINUE
IF (IPRINT.NE.2) GO TO 351

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PRINT 322
DO 430 K=1,NT
PRINT 323, YR(K), CITOT(L,M,K), CIRAT(L,M,K), AETOT(L,M,K),
*AERAT(L,M,K), SUC(L,K,1,1), SUC(L,K,1,2),
*SUC(L,K,1,3), SUC(L,K,1,8), SUC(L,K,1,9), SUC(L,K,1,10)
430 CONTINUE
PRINT 326
DO 431 K=1,NT
PRINT 323, YR(K), SUC(L,K,1,11), SUC(L,K,1,12), SUC(L,K,1,13),
*SUC(L,K,1,4), SUC(L,K,2,4), SUC(L,K,3,4), SUC(L,K,4,4),
*SUC(L,K,1,5), SUCS(L,K,1,1), SUCS(L,K,2,1)
431 CONTINUE
PRINT 327
DO 432 K=1,NT
PRINT 323, YR(K), SUC(L,K,2,5), SUC(L,K,3,5), SUC(L,K,4,5),
*SUCS(L,K,3,1), SUC(L,K,1,6), SUCS(L,K,1,2), SUCS(L,K,2,2),
*SUC(L,K,2,6), SUCS(L,K,3,2), SUC(L,K,3,6)
432 CONTINUE
PRINT 328
DO 433 K=1,NT
PRINT 323, YR(K), SUC(L,K,4,6), SUC(L,K,5,6), SUCS(L,K,4,2),
*SUCS(L,K,5,2), SUC(L,K,1,7), SUCS(L,K,1,3), SUC(L,K,2,7),
*SUC(L,K,3,7), SUC(L,K,4,7), AECID(L,M,K)
433 CONTINUE
351 CONTINUE
366 CONTINUE
PRINT 102
DO 361 K=1,NT
PRINT 101, YR(K), CIRAT(4,M,K), CITOT(4,M,K), AETOT(4,M,K),
*AERAT(4,M,K), AECID(4,M,K)
361 CONTINUE
500 CONTINUE
100 FORMAT(1H1, 3X, "RECHARGE M/YR", 3X, " FLUX M/YR  ",
*3X, "VELOCITY M/YR", 2X,
*"TRAVEL TIME YR", 2X, "25% FLUX CUM/YR", 2X, "2.5% FLUX", 5X,
* ".25% FLUX")
101 FORMAT(5X, 7(1PE10.2, 5X))
102 FORMAT(/ /8X, "TIME", 10X, "CIRAT", 10X, "CITOT", 10X, "AETOT",
*10X, "AERAT", 10X, "AECID")
103 FORMAT(/ /, "*****", 12, "TH MEDIUM *****")
300 FORMAT(10X, "UNDECAYED")
301 FORMAT(5X, A8, "GM=", 1PE10.2, 10X, "CI=", 1PE10.2)
302 FORMAT(80X, "TIME =", 1PE10.2)
307 FORMAT(15X, A8)
308 FORMAT(/49X, "RECHARGE RATE =", 1PE10.2, "(MM/YR)")
309 FORMAT(26X, "DISS RATE GM/YR", 4X, "CUM CI", 9X, "CUM GMS", 9X,
*"KGMS LEFT", 6X, "CUM CI/RL", 4X, "NRC-RATIO", 4X, "RTCUR")
310 FORMAT(17X, A8, 5(1PE10.2, 6X), 1PE10.2, 4X, 1PE10.2)

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311 FORMAT(3X,"CHAIN 1 - THORIUM SERIES")
312 FORMAT(3X,"CHAIN 2 - NEPTUNIUM SERIES")
313 FORMAT(3X,"CHAIN 3 - URANIUM SERIES")
314 FORMAT(3X,"CHAIN 4 - ACTINIUM SERIES")
315 FORMAT(3X,"ACTIVATION PRODUCTS")
316 FORMAT(3X,I3,3X,I3,3X,5(1PE10.2,5X),10X,"TIME =",1PE10.2)
317 FORMAT(17X,A8,16X,4(1PE10.2,6X),1PE10.2,4X,1PE10.2)
318 FORMAT(10X,3(1PE10.2,10X))
319 FORMAT(1H1,7X,"TIME",10X,"RECHARGE",10X,"TOTAL CURIES")
320 FORMAT(/1X,"====="/)
321 FORMAT(1X,"*****")
322 FORMAT(/2X,"TIME",2X,"TOTAL CURIES",2X,"DIS EPA RATIO",
*2X," AE-TOTAL ",2X,"AE-EPA RATIO",2X," C-14 AE ",2X,
*" TC-99 AE ",2X," I-129 AE ",2X," NI-59 AE ",2X,
*" CS-135 AE ",2X," SN-126 AE"/)
323 FORMAT(11(1PE10.2,2X))
325 FORMAT(99X,"RECHARGE RATE =",1PE10.2)
326 FORMAT(/,5X,"TIME",4X,
*" ZR-93 AE ",2X," SR-90 AE ",2X," CS-137 AE",
*2X," CM-244 AE",2X," PU-240 AE",2X," U-236 AE ",2X,
*" TH-232 AE",2X," CM-245 AE",2X," PU-241 AE",2X,
*" AM-241 AE"/)
327 FORMAT(/,5X,"TIME",4X," NP-237 AE",2X,
*" U-233 AE ",2X," TH-229 AE",2X," RA-225 AE",
*2X," CM-246 AE",2X," AM-242 AE",2X," CM-242 AE",2X,
*" PU-242 AE",2X," PU-238 AE",2X," U-238 AE "/)
328 FORMAT(/,5X,"TIME",4X," U-234 AE",2X," TH-230 AE",2X,
*" RA-226 AE",2X," PB-210 AE",2X," AM-243 AE",
*2X," NP-239 AE",2X," PU-239 AE",2X," U-235 AE ",2X
*"PA-231 AE",2X,"AECID"/)
9999 STOP
END
SUBROUTINE BAT(NCHNS,AL,T,NEC,CONI, TM21, TM31, TM41, TM32, TM42,
*TM43, TM51, TM52, TM53, TM54, CONN)
DIMENSION AL(5,14), TM21(14), TM31(14), TM41(14), TM32(14),
*TM43(14), TM42(14), EXT(5,14), NEC(14), CONI(5,14), CONN(5,14),
*TM51(14), TM52(14), TM53(14), TM54(14)
DO 2 I=1,NCHNS
N=NEC(I)
DO 2 J=1,N
CONN(J,I)=0.
Z=-AL(J,I)*T
IF(Z.GT.-1.E1000)GO TO 5
EXT(J,I)=0.
GO TO 6
5 EXT(J,I)=EXP(Z)
6 CONTINUE
2 CONTINUE

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DO 3 I=1,NCHNS
C1=CONI(1,I)
C2=CONI(2,I)
C3=CONI(3,I)
C4=CONI(4,I)
C5=CONI(5,I)
N=NEC(I)
CONN(1,I)=C1*EXT(1,I)
  IF(N.EQ.1)GO TO 4
X=AL(1,I)*TM21(I)*C1
Y=-X+C2
CONN(2,I)=X*EXT(1,I)+Y*EXT(2,I)
  IF(N.EQ.2)GO TO 4
X=AL(1,I)*AL(2,I)*C1
X1=X*TM21(I)*TM31(I)*EXT(1,I)
Y=-X*TM21(I)*TM32(I)+AL(2,I)*C2*TM32(I)
Y1=Y*EXT(2,I)
Z=X*TM31(I)*TM32(I)-AL(2,I)*C2*TM32(I)+C3
Z1=Z*EXT(3,I)
CONN(3,I)=X1+Y1+Z1
  IF(N.EQ.3)GO TO 4
X=AL(1,I)*AL(2,I)*AL(3,I)*C1
  Y=AL(2,I)*AL(3,I)*C2
X1=X*TM21(I)*TM31(I)*TM41(I)*EXT(1,I)
Y1=-X*TM21(I)*TM32(I)*TM42(I)
Y1=Y1+Y*TM32(I)*TM42(I)
Y1=Y1*EXT(2,I)
Z1=X*TM31(I)*TM32(I)*TM43(I)
Z1=Z1-Y*TM32(I)*TM43(I)
Z1=Z1+C3*AL(3,I)*TM43(I)
Z1=Z1*EXT(3,I)
W1=-X*TM41(I)*TM42(I)*TM43(I)
W1=W1+Y*TM42(I)*TM43(I)
W1=W1-AL(3,I)*C3*TM43(I)+C4
W1=W1*EXT(4,I)
CONN(4,I)=X1+Y1+Z1+W1
  IF(N.EQ.4)GO TO 4
A1=AL(1,I)*AL(2,I)*AL(3,I)*AL(4,I)*C1
A2=AL(2,I)*AL(3,I)*AL(4,I)*C2
A3=AL(3,I)*AL(4,I)*C3
  U=A1*TM21(I)*TM31(I)*TM41(I)*TM51(I)
  U=U*EXT(1,I)
  V=-A1*TM21(I)*TM32(I)*TM42(I)*TM52(I)
  V=V+A2*TM32(I)*TM42(I)*TM52(I)
  V=V*EXT(2,I)
  W=A1*TM31(I)*TM32(I)*TM43(I)*TM53(I)
  W=W-A2*TM32(I)*TM43(I)*TM53(I)
  W=W+A3*TM43(I)*TM53(I)

```

```
W=W*EXT(3,I)
X=-A1*TM41(I)*TM42(I)*TM43(I)*TM54(I)
X=X+A2*TM42(I)*TM43(I)*TM54(I)
X=X-A3*TM43(I)*TM54(I)
X=X+AL(4,I)*C4*TM54(I)
X=X*EXT(4,I)
Y=A1*TM51(I)*TM52(I)*TM53(I)*TM54(I)
Y=Y-A2*TM52(I)*TM53(I)*TM54(I)
Y=Y+A3*TM53(I)*TM54(I)
Y=Y-TM54(I)*AL(4,I)*C4
Y=(Y+C5)*EXT(5,I)
CONN(5,I)=U+V+W+X+Y
4 CONTINUE
3 CONTINUE
  RETURN
  END
```

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