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Nevada Nuclear Waste Storage Investigations Project

A First Survey of Disruption Scenarios for a High-Level-Waste Repository at Yucca Mountain, Nevada

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Prepared by Sandia National Laboratories Albuquerque, New Mexico 87185 and Livermore, California 94550 for the United States Department of Energy under Contract DE-AC04-76DP00789

Printed December 1987

"Prepared by Nevada Nuclear Waste Storage Investigations (NNWSI) Project participants as part of the Civilian Radioactive Waste Management Program (CRWM). The NNWSI Project is managed by the Waste Management Project Office (WMPO) of the U. S. Department of Energy, Nevada Operations Office (DOE/NV). NNWSI Project work is sponsored by the Office of Geologic Repositories (OGR) of the DOE Office of Civilian Radioactive Waste Management (OCRWM)."

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Printed copy: A08
Microfiche copy: A01

SAND85-7117
Unlimited Release
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Distribution
Category UC-70

A FIRST SURVEY OF DISRUPTION SCENARIOS FOR A HIGH-LEVEL-WASTE REPOSITORY AT YUCCA MOUNTAIN, NEVADA

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Under Sandia Contract 04-0961

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ABSTRACT

A high-level-waste repository located in unsaturated welded tuff at Yucca Mountain, Nevada, would rely on six different, although not entirely independent, barriers to prevent escape of radioactivity. These barriers are the waste canister, fuel cladding, dissolution of the spent fuel itself, and movement of released contaminants in three different hydrogeologic units: the unsaturated Topopah Spring welded tuff unit, the unsaturated Calico Hills nonwelded tuff unit, and the saturated tuff aquifer. Fifty-eight processes and events that might affect such a repository were examined. Eighty-four different sequences were identified by which these processes and events could lead to failure of one or more barriers. Sequences that had similar consequences were grouped into 17 categories: direct release, repository flooding, colloid formation, increased water flux through the repository, accelerated fracture flow, water diverted toward the waste package, accelerated dissolution mechanisms, accelerated cladding corrosion mechanisms, accelerated canister corrosion mechanisms, canister breakage, fracture flow in the Topopah Spring welded unit without increased moisture flux, reduced sorption in the Topopah Spring welded unit, water table rise above the Calico Hills nonwelded unit, fracture flow in the Calico Hills nonwelded unit, new discharge points, and faster flow in the saturated zone. The repository system has considerable redundancy; most of the more likely disruptions affect only one or a few barriers. Occurrence of more than one disruption is needed before such disruptions would cause release of radioactivity. Future studies of repository performance must assess the likelihood and consequences of multiple-disruption scenarios in order to evaluate how well the repository meets performance standards.

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PREFACE

This report was greatly improved by the advice and suggestions of colleagues. Discussions of specific questions with Elmer Klavetter, Schon Levi, Parvez Montazer, Virginia Oversby, Scott Sinnock, William E. Wilson, I. J. Winograd, and especially the project monitor, Martin Tierney, were most helpful. Barrie Klaits also contributed greatly as a research assistant. However, all conclusions are the author's alone.

1 INTRODUCTION

1.1 Purpose and Scope

The process of analyzing the long-term safety of a high-level-waste repository may be divided conceptually into a series of steps (modified from Koplik et al., 1982):

- A comprehensive list of processes and events that could contribute to release of radioactivity from a repository is assembled.
- Processes and events whose occurrence is not credible at the particular site being considered are eliminated.
- Ways in which each process or event could affect the performance of the repository are identified.
- A list of scenarios is selected for further analysis; in each scenario, the events and processes that control repository performance are specified.
- The likelihood of occurrence of each scenario is assessed.
- The consequences, should the scenario occur, are calculated.
- The results are evaluated to determine whether the repository is safe.

This report is directed to the second, third, and fourth of these steps, culminating in identification of scenarios, for a high-level-waste repository located in the unsaturated zone at Yucca Mountain, Nevada. The focus is on scenarios involving disruptive events and processes. Only the long-term performance of the repository in containing radioactivity is discussed; operational accidents are not addressed.

The purpose of this report is simply to identify the scenarios that require further analysis. A complete analysis of the scenarios is left for the future. Listing of a scenario here does not imply any definite conclusion about its likelihood or consequences; it simply means that information available to the author is insufficient to rule it out.

Some guidelines are needed to determine which scenarios must be considered. It is assumed here that scenarios need not be considered further if their occurrence in 10,000 years is highly unlikely (in the sense defined in EPA regulations [EPA, 1985]) or if they cannot lead to releases of 100 curies or more of radioactivity within 10,000 years after repository closure.

The report is written for readers who are already familiar with the geology and hydrology of the Yucca Mountain site. Index maps and a stratigraphic column are provided in Figures 1, 2, and 3. The discussion is based to a large extent on the draft statutory Environmental Assessment (DOE, 1984, referred to below as EA); readers not already familiar with the site should first read the relevant portions of the EA (in particular, Sections 3.2, 3.3, 6.3, and 6.4) or another general introduction such as Sinnock et al. (1984). Readers should also be familiar with the preliminary conceptual model of the Yucca Mountain unsaturated zone presented by Montazer and Wilson (1984) and summarized in Figures 4 and 5.

Listings of scenarios for a repository at Yucca Mountain have previously been published by Hunter et al. (1982; 1983). The work of Hunter et al. was completed when the stratum in which the repository was to be located had not yet been chosen and much less was known than is today about the hydraulic and geological properties of the site. As a result, the present report is able to be considerably more specific in describing scenarios. However, the failure mechanisms discussed by Hunter et al. are carefully considered, and those that Hunter et al. considered credible for a repository in the Topopah Spring unit are explicitly included or rejected.

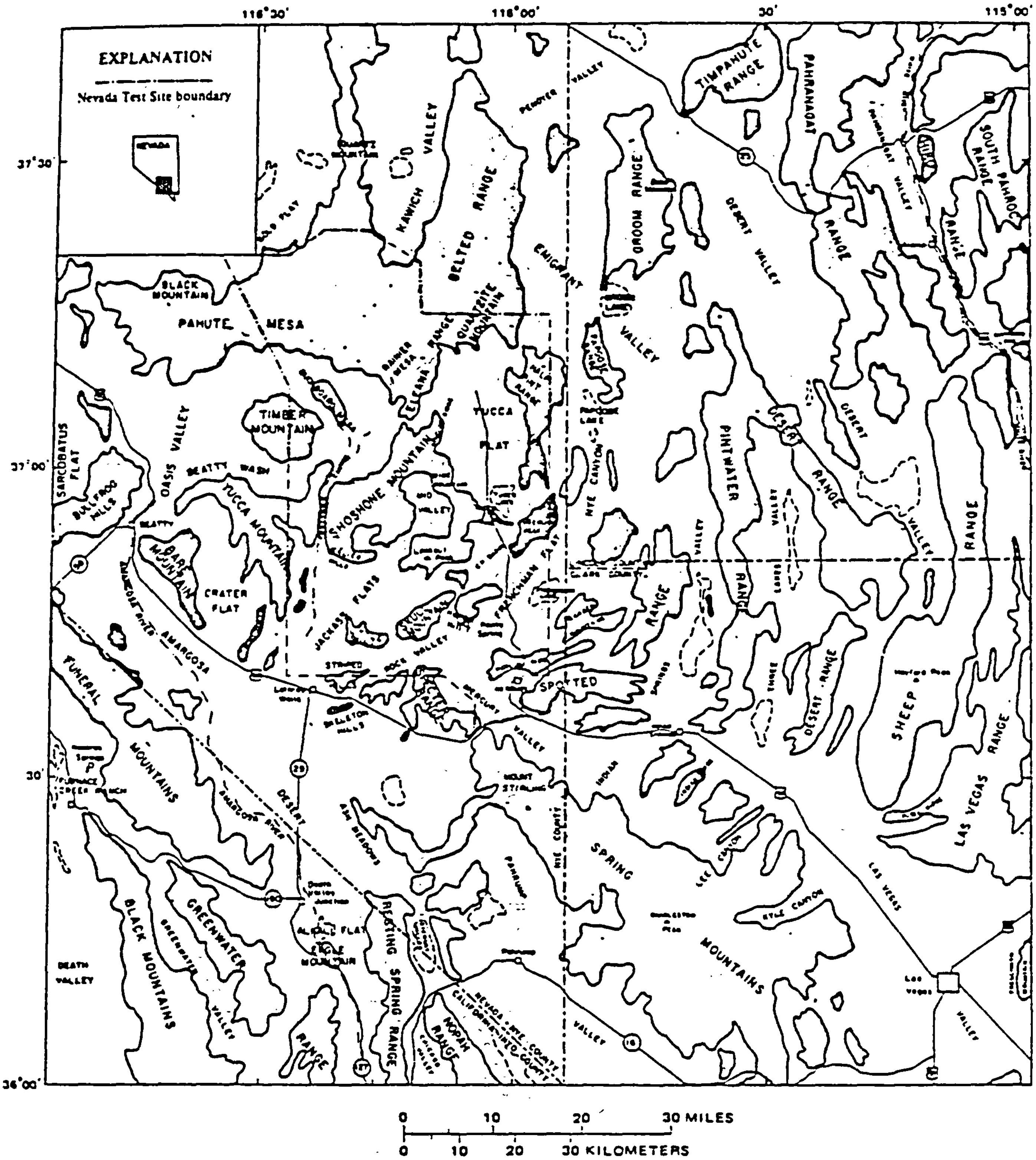

Figure 1. Index map showing topographic features of Nevada Test Site and vicinity.

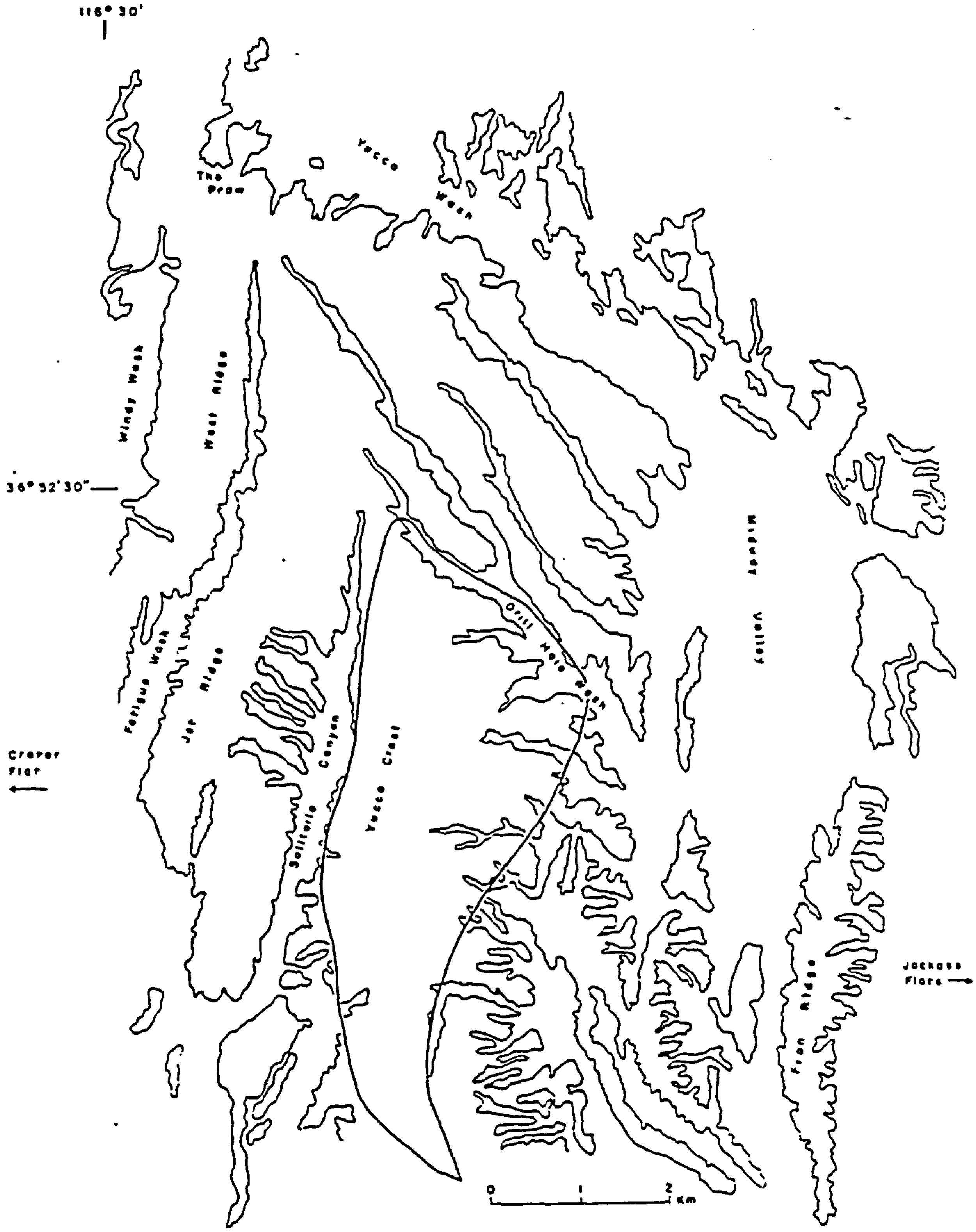

Figure 2. Index map of Yucca Mountain, showing contact of bedrock with alluvium. Heavy line outlines proposed repository site.

Stratigraphic unit		Tuff lithology	Hydrogeologic unit	Approximate range of thickness[1] (meters)	Fracture density[2] (fractures/m³)	Generalized permeability[3]	
						Matrix	Fracture
Alluvium		----	Alluvium	0-30	----	Generally substantial	----
Paintbrush Tuff	Tiva Canyon Member	MD	Tiva Canyon welded unit	0-150	10-20	Negligible	Substantial
Paintbrush Tuff	Yucca Mountain Member; Pah Canyon Member	NP, B	Paintbrush nonwelded unit	20-100	1	Moderate	Small?
Paintbrush Tuff	Topopah Spring Member	MD	Topopah Spring welded unit	290-360	8-40	Negligible	Substantial
Tuffaceous beds of Calico Hills; Crater Flat Tuff	Prow Pass Member	NP, B (V) / (D) (in part zeolitic)	Calico Hills nonwelded unit; Water table; Saturated zone	100-400	2-3	(V) Substantial / (D) Small to negligible	Small?
Crater Flat Tuff	Bullfrog Member	MD, NP, B (undifferentiated)	Crater Flat unit	0-200	8-25	Variable	Variable

[1]Thicknesses from geologic sections of Scott and Bonk (1984).
[2]Scott and others (1983).
[3]Inferred from physical properties.

Figure 3. Summary of hydrogeologic units present above the water table at Yucca Mountain (from Montazer and Wilson, 1984). (B, bedded; MD, moderately to densely welded; NP, nonwelded to partially welded; (D), devitrified; (V), vitric)

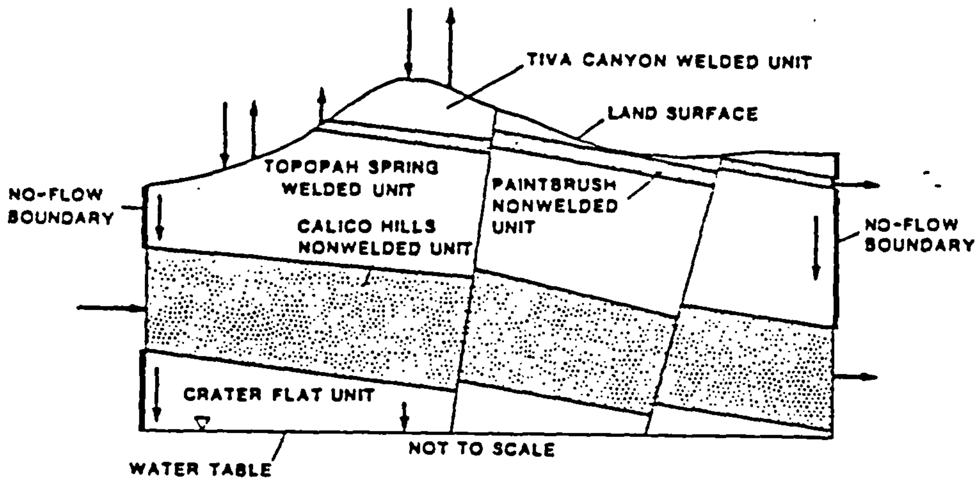

Figure 4. Generalized section across Yucca Mountain showing positions of flow boundaries and flux directions at the boundaries (from Montazer and Wilson, 1984).

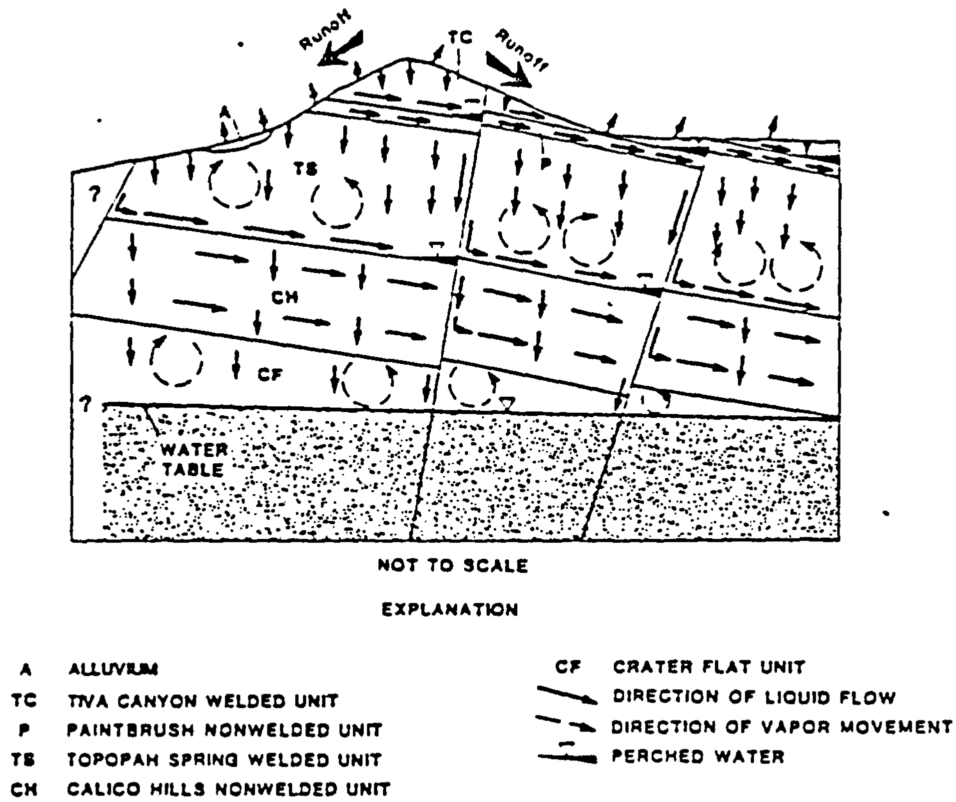

Figure 5. Generalized section across Yucca Mountain showing current flow regime in the conceptual model of Montazer and Wilson, (1984). Lengths of solid arrows show relative magnitude of fluxes.

The preliminary nature of this report requires emphasis. To conceive of everything that might happen in the next 10,000 years at Yucca Mountain is beyond the imagination of any individual, or of any small group of individuals. The list of scenarios to be included in performance assessments of a Yucca Mountain repository must be expanded and refined through the efforts of many individuals over the years of site characterization. Only through wide comment and intense peer review can a reasonably complete list of scenarios be obtained. All conclusions drawn in this report are solely the responsibility of the author.

1.2 Assumptions

The potential repository site addressed by this report is at Yucca Mountain, Nevada. The repository would be located in the unsaturated Topopah Spring Member of the Paintbrush Tuff. It would contain about 70,000 metric tons of spent fuel.

Six different barriers would impede release of radioactivity from such a repository to the human environment: canisters in which the spent fuel is packed, fuel cladding, the resistance to dissolution of the waste itself, movement downward through the Topopah Spring welded tuff unit in which the repository is located, movement downward through the underlying Calico Hills nonwelded tuff unit, and lateral movement through the saturated rocks underlying the repository. Beneath some parts of the proposed repository site, portions of the Prow Pass welded unit, Crater Flat nonwelded unit, and Bullfrog welded unit are unsaturated. For the purpose of describing general scenarios, these units serve approximately the same function as the Calico Hills nonwelded unit, and for simplicity they are not discussed here.

A seventh barrier would probably be present as well. This is the capillary barrier created by an air gap (or perhaps some coarse packing material) between the waste packages and the rock. Capillary forces impede the water in the rock matrix, which is under considerable suction, from leaving the matrix, so that an air gap would tend to keep the packages dry. However, the effectiveness of this barrier is at present poorly understood. It may be possible for moisture to wick onto the waste packages at points of contact with the rock, or perhaps to drip on the packages from above. Because of this uncertainty, the scenarios discussed in this report assume that the capillary barrier is in some way overcome. With further analysis, however, this barrier may be incorporated into our understanding of repository performance to provide an additional element of redundancy in the system.

The barriers are not completely independent; numerous causes can be imagined that would affect the performance of more than one barrier. Nevertheless, there is a good deal of redundancy in the system; in many scenarios where some barriers fail, other barriers still contain the wastes.

The unfolding of many disruptive scenarios depends on alternative conceptions of the present ground-water flow system, in both saturated and unsaturated zones. The "baseline" conceptual model, currently thought to best describe the flow system in the unsaturated zone, is that described by Montazer and Wilson (1984). Neither of these conceptual models has been fully confirmed, and alternatives cannot be definitively ruled out at this time. This report therefore does not assume that the current conceptual models are correct and addresses scenarios that would be disruptive if reasonable alternative conceptual models turn out to be true. Some alternative hypotheses used in the text are as follows:

- Flow through the Topopah Spring welded unit, instead of being limited to the rock matrix, goes through fractures.

- Areas of high moisture flux in the deep unsaturated zone are controlled not, as Montazer and Wilson (1984) suggest, structurally, but by the location of zones of greater infiltration.

- Ground-water velocities in the saturated zone are lower than calculated by the EA (Section 6.3.1.1.5). This might be because the true hydraulic gradient is less than the upper-bound estimate used in the EA, or because the regional average hydraulic conductivity is less than measured in well tests because of the presence of flow barriers.

Scenarios leading to release of radioactivity in gaseous form are not discussed here. The two principal nuclides that might escape as gases, carbon-14 and iodine-129, have inventories of approximately 800 and 33 curies per thousand metric tons of uranium, respectively, at closure (DOE, 1986, Table 6-47). (A substantial inventory of krypton-85 is also present at closure, but its half-life of 10.72 years implies that the inventory will decline by more than eight orders of magnitude within 300 years. Other noble-gas fission products have even shorter half-lives [Kocher, 1981].) Both iodine and carbon dioxide are soluble in water, and futhermore iodine has a fairly low vapor pressure at ambient temperatures. Gases in unsaturated rocks are in extremely intimate contact with moisture, and chemical equilibrium for dissolution of gases in water can safely be assumed. It thus seems highly likely that any gases released from spent fuel will quickly enter solution. Consequently, releases of radioactivity by gas-phase migration will not be considered in this study. Some additional analysis of the chemistry involved would be desirable to verify this conclusion.

At this stage of the repository program, detailed designs for the repository and for waste packages have not yet been chosen. This report will therefore be more useful to the extent it is applicable to a variety of designs. Nevertheless, some specificity is necessary to focus on site- and design-specific scenarios while keeping the task at hand to a manageable size. The following assumptions have therefore been made about the design of the repository and waste packages:

- Only spent fuel and not reprocessing waste is disposed of in the repository.

- The repository is constructed only in the "primary repository area" (Figure 1) and not in the extension areas outlined in Figure 3-8 of the EA.

- The waste is enclosed in metal canisters designed to prevent any release of radioactivity during an initial period. These canisters are emplaced directly in vertically or horizontally drilled holes, without clay or other porous backfill around them. (Porous backfill might be placed inside the canisters, as in one of the waste package designs described by Gregg and O'Neal [1983].)

A full understanding of release scenarios for a radioactive-waste repository requires collaboration among many technical disciplines. In some cases, our knowledge is insufficient to determine whether a particular scenario is credible. To maintain conservatism in such situations, scenarios are not ruled out without convincing reason. As a result, the report probably includes some scenarios that experts in the relevant fields will find not credible. Such scenarios can be eliminated in future stages of the scenario-screening process.

1.3 Organization of the Report

The report is based on a list of relevant phenomena published by a working group of the International Atomic Energy Agency (IAEA, 1983). In Chapter 2, the likelihood that each process or event on the list will occur at Yucca Mountain is assessed. For credible events, mechanisms are identified by which wastes could be transported directly to the accessible environment or by which transport by ground water could be accelerated. Some of those mechanisms are ruled out immediately on the basis of simple physical arguments. The remaining mechanisms are formulated as descriptions of possible future sequences of events. A scenario analyzed in a future performance assessment might involve one of these sequences, or it might involve several occurring at the same time.

In Chapter 3, the sequences are classified according to their effects on the different release barriers in the Yucca Mountain system. Scenarios with differing causes but similar consequences are grouped so that their consequences can be analyzed together.

In Chapter 4, the effects of each group of failure sequences are examined to determine what combination of failures is necessary for radioactivity to be released. These combinations constitute the scenarios that must be analyzed in future performance assessment work. Methods for further analysis of these scenarios are also recommended in this chapter.

General conclusions and recommendations for further work are given in Chapter 5.

2 ELEMENTARY PROCESSES AND EVENTS

This chapter discusses the various processes and events that form the bases of release scenarios and identifies sequences by which they can cause complete or partial failure of one or more barriers to radionuclide release. The discussion is based on a list of 57 events and processes published by the International Atomic Energy Agency (IAEA, 1983), and included here as Table 1. The IAEA compilation incorporates previously published listings of phenomena that might affect a high-level-waste repository (Burkholder, 1980; Koplik et al., 1982) and is the most complete published list. Since its compilation, one additional process, that of microbial growth, has come to the attention of the research community. Each of these 58 events and processes is discussed individually below. They are treated in the order of the IAEA list, with microbial growth added at the end.

For each process, we first discuss its likelihood of occurrence. For those processes whose occurrence is credible, we describe possible barrier-failure sequences in two categories: those leading to direct releases of radioactivity and those that could indirectly enhance releases by ground-water transport.

The discussion of each elementary phenomenon concludes with a listing of any barrier-failure sequences that appear to be of possible importance in leading to releases of radioactivity. For readability, the events in each sequence are stated in the present tense without using conditional verb forms. This is not meant to imply that the events will happen or that one event will lead to another. The sequences are purely hypothetical; their inclusion here means only that we do not have enough information to show that they are not credible; it does not imply that we think them credible.

Simple physical arguments can be used to eliminate some sequences immediately because of their improbability or insignificant consequences. When such arguments are available, they are presented or previous publications are cited.

Table 1

IAEA list of phenomena potentially relevant to scenarios for radioactive-waste repositories

Natural processes and events	
Climatic change	Uplift/subsidence
Hydrology change	• Orogenic
Sea-Level change	• Epeirogenic
Denudation	• Isostatic
Stream erosion	Undetected features
Glacial erosion	• Faults, shear zones
Flooding	• Breccia pipes
Sedimentation	• Lava tubes
Diagenesis	• Intrusive dikes
Diapirism	• Gas or brine pockets
Faulting/seismicity	Magmatic activity
Geochemical changes	• Intrusive
Fluid interactions	• Extrusive
• Ground-water flow	Meteorite impact
• Dissolution	
• Brine pockets	

Human activities	
Faulty design	Undetected past intrusion
• Shaft seal failure	• Undiscovered boreholes
• Exploration borehole seal failure	• Mine shafts
Faulty operation	Inadvertent future intrusion
• Faulty waste emplacement	• Exploratory drilling
Transport agent introduction	• Archaeological exhumation
• Irrigation	• Resource mining (mineral, water, hydrocarbon, geothermal, salt, etc.)
• Reserviors	Intentional intrusion
• Intentional artificial Ground-water recharge or withdrawal	• War
• Chemical liquid waste disposal	• Sabotage
Large-scale alterations of hydrology	• Waste recovery
	Climate control

Table 1

IAEA list of phenomena potentially relevant to scenarios for radioactive-waste repositories (concluded)

Waste and repository effects	
Thermal effects • Differential elastic response • Nonelastic response • Fluid pressure, density viscosity changes • Fluid migration Mechanical effects • Canister movement • Local fracturing	Chemical effects • Corrosion • Waste package-rock interactions • Gas generation Radiological effects • Material property changes • Radiolysis • Decay-product gas generation • Nuclear criticality

Most of the processes and events affect releases of radioactivity only by perturbing the ground-water system, above or below the water table. These phenomena obviously cannot lead to direct releases, and so the section on direct releases is omitted from the relevant sections.

The sequences listed in this chapter are at times rather repetitive. This is because different causes (natural and artificial climate change, for example) can have very similar effects. The reader is asked to bear with us for the sake of completeness; in Chapter 3 sequences with similar effects will be grouped, and henceforth they can be treated together.

2.1 Natural Phenomena

2.1.1 Climate Change

Likelihood of occurrence--The climate in the Yucca Mountain area is expected to change over the next 10,000 years (Spaulding, 1983). Initially, one expects a warming due to the "greenhouse effect" of increased atmospheric carbon dioxide. This could be accompanied by an increase in summer precipitation of probably less than 50 percent. Subsequently, the onset of a cooler and wetter "pluvial" period is expected, but conditions in the next 10,000 years are not expected to be as severe as at the Wisconsin maximum 18,000 years ago (when winter precipitation was 60 percent to 70 percent higher and winter temperatures were at least 6° C lower than at present). There is evidence (Winograd et al., 1985) for a long-term trend toward greater aridity and lower water tables in the area, with the cycles of pluvial and arid periods presumably superimposed in this trend.

Indirect releases--The principal way in which climate change could affect repository performance is by changing the rate of ground-water infiltration. This could lead to increased moisture flux through the repository, shorten the flow path in the unsaturated zone by raising the water table, or increase ground-water velocities in the saturated zone. Winograd and Doty (1980) discuss effects of greater infiltration on the performance of a radioactive-waste repository. This section will first discuss the likely magnitude of changes in recharge and then address their effects on the barriers to radionuclide release.

Claassen (1983) argues that current recharge in the area just downgradient of Yucca Mountain is negligible and that the ground water of the area recharged from snowmelt flowing in stream channels during the latest Pleistocene and early Holocene, about 10,000 years ago. This suggests a strong influence of changing climate on ground-water conditions.

The magnitude of increased recharge in the warming period in the immediate future should be less than 50 percent, because summer precipitation contributes less recharge than winter precipitation. If, as is possible, summer precipitation contributes negligibly to recharge, there would be no increase in recharge at all. During the subsequent pluvial, maximum recharge should be bounded by what occurred during the last 100,000 years. Czarnecki (1984) points out that empirical relationships describing current recharge conditions in Nevada suggest that as precipitation increases in a pluvial, a higher percentage of it infiltrates as recharge. This is reasonable given the cooler temperatures that prevail both at higher altitudes and during pluvial periods.

An increase in recharge at the repository site would increase the water flux through the unsaturated zone. This might reduce canister lifetimes, increase waste-dissolution rates, and reduce the travel time of contaminants from the repository to the water table.

In considering effects of increased percolation rates on waste-package performance, care should be taken to understand what percolation rates are implicitly assumed in baseline estimates of performance. For example, canister-corrosion tests may be carried out in wetter environments than are expected in the repository. An increase in percolation might not expose canisters to more water than did the tests from which lifetimes are estimated.

If an increase in percolation is sufficient to cause spatially continuous fracture flow in tuff units in which matrix flow now dominates, the reduction in ground-water travel time will be very large. It should be remembered that travel times of radionuclides that potentially might be released into the ground-water system may be significantly longer than the travel time of the ground water itself.

Increases in recharge at other locations within the ground-water basin could also affect performance. With more recharge upgradient of the repository, hydraulic gradients would increase, raising the velocity of ground-water movement.

Greater recharge anywhere in the basin would tend to raise the water table. A higher water table would reduce the path length through the unsaturated zone, thus reducing ground-water travel times. If the water table were to rise above the top of the Calico Hills nonwelded hydrogeologic unit, the largest component of the travel time as now estimated would be eliminated. Only the absence of fracture flow in the Topopah Spring welded unit could sustain the long travel time now postulated for the unsaturated zone.

A higher water table might cause a major change in the saturated-zone hydraulic regime. In a conceptual model in which ground-water flow is controlled by hydraulic barriers, a fracture zone or zone of permeable alluvium might cross a barrier above the current water table. If the permeable zone were to be saturated, the barrier would be short-circuited, and the volume of flow across it could increase drastically. The effect would be similar to the "spillway" that Waddell et al. (1984, p. 36) describe in alluvium overlying the lower clastic aquitard at Oasis Valley (see also Claassen, 1983, p. 42). Creation of a "spillway" might greatly affect flow velocities in the surrounding region.

Regionally higher ground-water levels might also create new discharge points closer to the repository, thereby reducing the distance to the accessible environment. However, any new discharge points much closer than 10 kilometers from the repository would be above the repository. Given the absence of regional confining beds, this implies that discharge could occur at such locations only if the repository flooded.

An extreme rise in the water table that flooded the repository would drastically affect the performance of the waste package and eliminate the unsaturated zone as a flow barrier. For reasons given in the EA (Section 6.3.1.4.4) and according to Czarnecki's (1984) calculations, this scenario is very dubious. Further investigation of the lakebed and spring deposits above the repository level in southern Crater Flat described by Hoover et al. (1981) would be desirable in order to fully rule out this possibility.

With greater infiltration, perched-water conditions might develop in particular fracture zones or at the top of nonwelded hydrogeologic units. Some perching seems to occur even under present recharge conditions. Perched water was probably detected at the base of the Topopah Spring Member in Well H-1 (Rush et al., 1984). A "small seep" issued from the welded Topopah Spring unit, about 80 meters above its base, in Well H-3 (Thordarson et al., 1985). At Rainier Mesa, where present-day percolation seems to be greater than at Yucca Mountain, extensive perching of young (0.8- to 6-year-old) water occurs in the zeolitized tuffaceous "tunnel beds" (Thordarson, 1965). It is notable, however, that Thordarson observed little or no perching in the welded tuffs above the tunnel beds.

A perched water table might create new ground-water discharge locations close to the repository. Radioactivity could not, however, be released at such discharges. If the perched zone were above the repository, the water would not have contacted the waste. A perched zone below the repository could not discharge within the controlled zone, because the repository will be below the level of Crater and Jackass Flats.

Through a perched water table, percolating water could be diverted laterally to flow rapidly down through a narrow fracture zone. If the perched water were above the repository, a zone of high flux through the repository could be created. If the perching occurred below the repository, most likely at the lower contact of the Topopah Spring welded unit, the zone of enhanced flow would pass only through the Calico Hills nonwelded unit.

Flooding of the repository by perched water is extremely unlikely because the repository will be located in the very well drained Topopah Springs welded unit, far above its contact with the underlying nonwelded unit.

Sequences to be considered--The following sequences require further consideration:

1. An increase in infiltration at the repository site increases the unsaturated water flux through the repository. This reduces canister lifetimes, increases waste-dissolution rates, and, by causing fracture flow in the welded Topopah Spring unit, increases contaminant velocity in the unsaturated zone.

2. An increase in recharge raises the water table beneath the repository above the top of the Calico Hills nonwelded tuff unit. If fracture flow is initially present in the Topopah Springs welded unit or is induced by the same climate change, this would drastically reduce ground-water travel times in the unsaturated zone.

3. A higher water table short-circuits a flow barrier in the saturated zone, changing the pattern of flow.

4. Regionally higher water tables create discharge points closer to the repository, reducing the distance to the accessible environment. The rise in the regional water table floods the repository. (The many further scenarios that could arise from

this are not elaborated here, on the assumption that further work will show this event not to be credible.)

5. Perched water develops above the repository, diverting downward flow through the repository into localized zones. Some waste canisters are wetted more than the others, affecting canister lifetimes and leach rates.

6. Perched water develops at the base of the Topopah Spring welded unit. Flow through the Calico Hills unit is diverted into fracture zones draining the perched water table.

2.1.2 Hydrology Change

While it is possible for the hydrogeology of the area to change, this would occur as a consequence of some other cause, such as fault movement, climate change, etc. Changes in surface-water hydrology, which would change the boundary conditions for the ground-water system, would also result from other causes, climate change in particular. Hydrology changes are involved in the great majority of the indirect release scenarios discussed throughout the report. There would be no point in repeating all of this material here.

2.1.3 Sea-Level Change

Likelihood of occurrence--Sea-level change has occurred throughout the Quaternary as a consequence of glaciation and other causes.

Indirect releases--Yucca Mountain and vicinity are part of the internally drained Death Valley ground-water basin system. Base levels for streams and ground-water discharge are set by the elevation of Death Valley and nearby topographic features, and not by sea level. The magnitude of past and anticipated sea-level changes is far less than what would be required to flood Death Valley and change this situation. Therefore sea-level changes will not lead to increased radionuclide releases.

2.1.4 Denudation

The discussion of denudation here deals only with general lowering of the land surface, as opposed to localized erosion in stream channels, which is discussed in the next section.

Likelihood of occurrence--Denudation, or the general lowering of the earth's surface by wind and water erosion and such related processes as alternating extremes of hot and cold weather, is certain to occur in an area with the topographic relief of Yucca Mountain.

Direct releases--A direct release due to denudation would require removal of the entire mountain above the repository and lowering of the land surface to the level of the repository. Average Quaternary stream erosion rates, which would be expected to exceed denudation rates, are less than 0.0001 meter per year (USGS, 1984). At this rate, less than 1 meter of denudation would occur in the 10,000-year period that this study addresses. This compares with a depth of more than 200 meters to the repository (EA, Section 6.3.1.5). Winograd (1974) cites very similar rates--90 to 180 centimeters in 10,000 years--as typical denudation rates in arid and semiarid climates.

Denudation rates could be increased by a change in climate or by increases in topographic relief due to uplift or subsidence. However, the Quaternary uplift rate at Yucca Mountain is less than 30 centimeters in 10,000 years (EA, Section 6.3.1.7.4), and elsewhere in the southwestern Great Basin, uplift rates are no more than 4 (EA, Section 6.3.1.7.4) to 8 (NRC, 1985, p. 92) meters in 10,000 years.

Indirect releases--Denudation could affect water movement in either the saturated zone or the unsaturated zone.

To affect saturated flow, denudation would have to reach the water table at Yucca Mountain or at some other point in the ground-water basin. The water table lies below the repository, so the argument against direct release by denudation also excludes erosion to the water table at the repository site. At upgradient points, depths to water are similar to those at Yucca Mountain, and denudation is very unlikely to expose the water table. Downgradient, at discharge points, the water table lies close to the surface, but these correspond to topographic lows where aggradation is more likely than denudation.

Scenarios in which flow in the unsaturated zone is affected may be derived from the conceptual model of Montazer and Wilson (1984). In the model, downward flux through the Topopah Spring welded unit is much less than net infiltration because of lateral diversion of flow at the contact between the overlying nonwelded tuff unit and the welded tuff above it.

In the cross sections of Scott and Bonk (1984), both the Paintbrush nonwelded tuff unit and the Tiva Canyon welded unit overlie the Topopah Spring unit at all locations in the repository block, except in Drill Hole Wash at its northeastern boundary where the Tiva Canyon has been eroded through. The minimum thickness for these units shown on the cross sections is about 25 meters, with the welded unit sometimes only a few meters thick (in Scott and Bonk's Section CC', at the southern end of the repository block). These thicknesses are still sufficient to exclude significant changes from denudation during the 10,000-year period addressed by this study.

2.1.5 Stream Erosion

Likelihood of occurrence--The current topography of Yucca Mountain has been strongly shaped by stream erosion (Scott et al., 1984). As climates change over the next 10,000 years, there is an excellent chance that episodes of stream erosion will occur in the intermittently flowing washes on its slopes. Hoover et al. (1981) state that a period of arroyo-cutting began about 1840 and appears to continue to the present. Warming, increased summer precipitation, and any movement along basin-and-range faults would all tend to further encourage erosion (USGS, 1984). Since the washes are well entrenched in bedrock, it is extremely unlikely that their courses will undergo major changes, and it can be assumed that stream erosion will take the form of further entrenchment and broadening of existing canyons.

Hoover et al. (1981) report 70 centimeters of erosion in a wash in the last 140 years. Extrapolation of this rate over 10,000 years is probably unreasonable, but would suggest an upper bound of 50 meters on the next 10,000 years of erosion in the Yucca Mountain washes.

Entrenchment of the Amargosa River channel is also possible, because of the geologically recent integration of its drainage with Death Valley. The likely consequence of such erosion is a lowering of base levels and therefore of water tables (Winograd and Doty, 1980).

Direct releases--Direct release requires erosion down to the level of the repository. As discussed in the previous section, this is extremely unlikely.

Indirect releases--The saturated flow path could, in principle, be affected by erosion anywhere in the ground-water basin. However, given the deep water tables in most of the basin and the large head differences between recharge and discharge areas, an unreasonably large amount of erosion upgradient or near the repository would be required to change boundary conditions sufficiently to make an appreciable difference to the gradients near Yucca Mountain.

Downgradient erosion cannot be so easily neglected. Entrenchment of the Amargosa River Channel near Alkali Flat might increase hydraulic gradients and ground-water velocities. At the same time, it would lower the water table and improve the effectiveness of the unsaturated zone as a barrier. An evaluation of the magnitude of these two effects would require a better understanding of the hydraulics of the Alkali Flat-Furnace Creek Ranch ground-water basin than is now available.

To affect the unsaturated zone, stream erosion would have to occur at Yucca Mountain itself. If washes whose beds now lie on the Tiva Canyon welded tuff erode through that unit and entrench themselves in the Paintbrush nonwelded unit below, any lateral flow through the Tiva Canyon will be intercepted, and the depressions in the surface of the nonwelded unit will become favorable locations for enhanced flux through the Topopah Spring. This will be true to an even greater degree if the stream bed lies in the Topopah Spring itself.

Sequences to be considered--The following sequences require further consideration:

7. Entrenchment of the Amargosa River at Alkali Flat lowers base levels and increases regional gradients. Regional hydraulic relations are such that water-table lowering at Yucca Mountain is insignificant, but increases in ground-water velocity are significant.

8. Beds of intermittent streams now resting on the Tiva Canyon welded tuff unit erode through to the underlying nonwelded unit. These washes form a barrier to lateral flow in the Tiva Canyon and divert flow downward. Regions of high flux are formed below them.

2.1.6 Glacial Erosion

There is no evidence for past glaciation in the area of Yucca Mountain. As future climates are expected to resemble those experienced during the Quaternary, scenarios involving glacial erosion need not be considered.

2.1.7 Flooding

Likelihood of occurrence--During rainstorms, especially severe summer thunderstorms, flooding occurs in the washes draining Yucca

Mountain to the east (Squires and Young, 1984). Some of these washes lie above the repository site.

Indirect releases--Infiltration of floodwaters in arroyos may be a source of recharge to the ground-water system at Yucca Mountain. But other interpretations of recharge in the area are possible. Waddell et al. (1984) state that

> One hypothesis is that more recharge occurs beneath washes than beneath surrounding ridges, because water is concentrated in washes during runoff events. However, alluvium in washes may store the water at a shallow depth until evaporative mechanisms become active again after the storm has passed and humidity has decreased. A second hypothesis is that water that is intercepted by open fractures in surficial bedrock may move rapidly to a depth where evaporative forces are very small, and it may actually contribute more to total recharge than water that infiltrates beneath washes.

Claassen (1983) argues that "Numerous small floods . . . do not result in recharge" and that present-day ground waters are derived from seasonal flows of snowmelt at the end of the Pleistocene, thousands of years ago.

The conceptual model of Montazer and Wilson (1984) assumes that the areas under the washes are not, in general, areas of higher moisture flux through the Topopah Spring welded unit. In this model, rather, most water infiltrating through the washes moves laterally when it encounters the capillary barrier of the Paintbrush nonwelded unit above the Topopah Spring. The areal distribution of moisture flux in the Topopah Spring is controlled by structure rather than surface topography.

Current knowledge does not rule out the possibility that Montazer and Wilson are wrong on this point and flux through the Topopah Spring comes mostly from infiltration directly above. If this is the case, and if infiltration is concentrated in washes, zones of greater flux would underlie the washes. These zones might be permanently, seasonally, or intermittently wetter, depending on the frequency of recharge events. The depth to which zones of intermittent wetness would extend, if they exist, is at present unknown, and available information is insufficient to determine whether the time-variability would extend to repository depth.

One might try to combine the alternative models sketched above by suggesting that infiltration from the usual floods on Yucca Mountain is effectively diverted by capillary barriers and does not proceed directly to the Topopah Spring welded unit, but in very rare major floods so much water infiltrates that the capillary barrier is overcome and percolation is greatest beneath washes.

Whether this last scenario is consistent with the conceptual model of Montazer and Wilson is unclear. Flow can be diverted laterally by either or both of two capillary barriers. If there is flow in the fractures of the Tiva Canyon welded unit, it will have greater effective hydraulic conductivity than the underlying Paintbrush nonwelded unit. The Paintbrush unit in turn has greater effective hydraulic conductivity than the Topopah Spring welded unit if the latter has no flow in its fractures. The first of these capillary barriers should become more effective with increasing saturation; the wetting of fractures as water content rises would increase the contrast in effective hydraulic conductivity between welded and nonwelded units, which is the basis of the capillary barrier effect. The second capillary barrier should become less effective with increasing saturation, for the same reason. The relative importance of the two capillary barriers, if they operate at all, is unknown.

It is also possible that infiltration occurs on the mountain, <u>everywhere</u>, mostly after very infrequent major precipitation, the usual year-to-year precipitation being removed by evapotranspiration. If this is the case, the current moisture state measured in the field would not reflect a steady state driven by current precipitation, but rather a transient response to an event tens, hundreds, or even thousand of years ago.

Sequences to be considered--The following sequences require further consideration:

9. Flooding of the washes on Yucca Mountain by rainstorms is a major source of infiltration. Capillary barriers are ineffective in diverting this flux, and so zones of higher moisture flux exist permanently or seasonally below washes. One or more of these zones is not detected during site characterization.

10. Under usual moisture conditions, capillary barriers divert infiltration under major washes laterally. However, occasional major floods provide sufficient infiltration to overcome the capillary barrier and create temporary wetter zones beneath the washes.

11. Most percolation through the deeper unsaturated portions of Yucca Mountain occurs following major precipitation events whose recurrence interval is tens, hundreds, or thousands of years. Current moisture conditions on the mountain reflect the later, dryer stages of the response to one of these events. After future events, there are periods of tens to hundreds of years during which percolation through the unsaturated zone is increased. Fracture flow then occurs in the Topopah Spring unit and perhaps other hydrogeologic units between the repository and the water table.

2.1.8 Sedimentation

The processes of erosion and, to a lesser extent, sedimentation in washes are proceeding actively on Yucca Mountain. The mountain is under going net erosion. The sedimentation that will occur during the next 10,000 years will not differ in character from that which has occurred in the past and therefore should not significantly affect a repository.

2.1.9 Diagenesis

Because the repository is located in consolidated volcanic rocks, diagenetic processes as such are unlikely to be significant. However, a closely related geochemical process, the alteration of volcanic glass to a series of clay minerals, may be important. This is discussed in Section 2.1.12.

2.1.10 Diapirism

Diapirism generally refers to the flow of salt rocks. No salt formations are present in the subsurface at Yucca Mountain, nor are there shales, which have also been known to flow. Diapirism is therefore impossible at this site.

2.1.11 Faulting and Seismicity

The IAEA lists "faulting/seismicity" as a single phenomenon. However, movement along a fault within the repository could affect waste isolation in ways fundamentally different from events elsewhere that only send seismic waves through the repository. Since underground structures are generally resistant to earthquake effects [EA, Section 6.3.1.7.5], the waste package is designed to withstand a 20-foot drop onto an unyielding surface [Gregg and O'Neal, 1983], which would accelerate it far more than the 0.4 g expected from a maximum earthquake (EA, Section 6.3.1.7.5), and since the rocks of Yucca Mountain have already been subjected to earthquake stresses for millions of years, it is difficult to see how seismic waves from earthquakes centered outside the site could impair long-term waste isolation. (The report edited by Tsang and Mangold [1984, pp. 58-59] suggests otherwise, but in such general terms that it is difficult to derive any specific scenarios from it.) The discussion here will therefore focus on fault movement in or near the repository.

Even after movement stops, a new fault might perturb the ground-water flow system. The effects of a new fault on which movement had stopped would be similar to those of an existing, undiscovered fault at the same location, although surface mineralization or fill that might be present in an existing fault would be absent. Hydraulic effects of faults at locations where an existing fault would be sure to be discovered during site characterization are discussed in this section. At other locations, an existing undiscovered fault is more likely than a new one, given the great age of the tuffs compared to the 10,000-year period of this study. Faults at such locations are discussed in Section 2.1.19.

Likelihood of occurrence - Studies by the U.S. Geological Survey [USGS, 1984] conclude that stresses measured in drill holes at Yucca Mountain "are close to those at which frictional sliding might be expected to occur on the faults which strike N 25° E to N 30° E." Most faults and fractures in the area strike either northwest or north-northeast, so such faults are not numerous. Nevertheless, this stress state suggests the possibility of movement along either some existing fault or a new fault. The suggestion is borne out by the observation of Quarternary movement along at least one fault in Crater Flat [Swadley and Hoover, 1983]. Motion along existing faults is more likely than the creation of new faults.

The EA [Section 6.3.1.7.4] indicates that "a preliminary conclusion could be made that the north-trending faults at Yucca Mountain should be considered potentially active even though the absence of seismic activity suggest that they are not active." Calculations in Section 6.3.1.7.5 of the EA suggest rates of large earthquakes (magnitude greater than 6.5) of 0.01 to 0.025 per 1000 years per 1000 square kilometers, or 0.0006 to 0.0015 in 10,000 years for a 6.15-square-kilometer repository. Fault movements causing earthquakes of lesser magnitude are more likely.

Direct releases - One direct-release scenario is uplift of one side of a fault through a repository that is so rapid that waste is exhumed. Rates of fault movement in the area are no more than about 0.001 centimeter per year [EA, Section 6.3.1.7.5]. This yields a maximum uplift of 10 centimeters in 10,000 years, which would be insufficient by many orders of magnitude to bring waste to the surface.

Indirect releases - Movement along a fault could affect ground-water flow in several ways. The hydraulic conductivity of the fault itself could be increased by fracturing, brecciation, or dilatation of existing fractures, or it could be decreased by formation of fault gouge.

Small offsets on new faults through the Tiva Canyon welded unit could create "traps" for laterally moving moisture and thus new zones of enhanced flow through the Topopah Spring unit. Because rocks in the fault would be weakened, new arroyos might be formed by erosion at the surface, creating zones of enhanced infiltration. Large vertical offsets might place nonadjacent beds in contact, bypassing flow barriers, and they could create discontinuities in aquifers. But the hydrologic units are thick enough that scenarios of the latter type require grossly excessive fault offsets, even for the unsaturated-zone units (the Tiva Canyon and the underlying Paintbrush nonwelded unit) that in places have thicknesses of only a few tens of meters.

Movement along a fault through the repository might also shear waste canisters open.

Sequences to be considered--The following sequences require further consideration:

12. Movement of a new or existing fault shears canisters along the line of the fault. The same fault also creates a "trap" for moisture moving laterally through the Tiva Canyon welded unit, and so the sheared canisters are placed in a region of enhanced downward moisture flux.

13. Fracture dilatation along a new or existing fault creates zones of enhanced premeability in the Calico Hills and Paintbrush

nonwelded units. Erosion of an arroyo at the surface and increased hydraulic conductivity of the Paintbrush unit create a zone of increased percolation along the fault. Moisture moves through fractures along the fault in the Topopah Spring and Calico Hills units. The result is a greatly reduced unsaturated-zone travel time.

14. The downdip side of a new or existing fault moves up. The fault thus forms a "trap" for laterally moving moisture in the Tiva Canyon welded unit. A new region of enhanced flux through the Topopah Spring unit is created.

15. Fracturing along a newly mobilized fault creates a permeable pathway through the flow barrier north of the repository block. The magnitude of the resulting change in the flow system is sufficient to raise the water table under the repository to the top of the Calico Hills nonwelded unit. Hydraulic gradients increase also. This decreases travel times in both saturated and unsaturated zones by eliminating the section of the unsaturated flow path through the Calico Hills and by raising the saturated hydraulic gradient.

16. As in the previous scenario, fault-caused fracturing breaches the flow barrier north of the repository block. Flow is blocked by another barrier, not apparent from the current head distribution, and the resulting rise in water table floods the repository. The water passing through the repository discharges through springs in Fortymile Wash.

2.1.12 Geochemical Changes

Geochemical processes could be accelerated by waste and repository effects, and so they are discussed in more detail in Section 2.3. The discussion here is limited to processes occurring away from the zone of thermal influence, especially below the water table.

Likelihood of occurrence--The principal geochemical alteration processes occurring on Yucca Mountain are the devitrification of glassy components of the tuff and their alteration to a series of zeolite minerals. Historically, these processes have not occurred at significant rates in the proposed repository horizon. They have occurred below the repository.

Indirect releases--These geochemical processes could either improve or degrade waste isolation. The principal improvement in isolation would be due to formation of alteration products, which generally have chemical properties giving better sorption than the original minerals. The potential for poorer isolation would be due to reduction of effective porosity by precipitation in the saturated zone. Intuitively, it would appear that the improvement of isolation because of better sorption would outweigh any loss of effective porosity (EA, Section 6.3.1.1.4), but no quantitative evaluation has been conducted to determine whether that would be so (NRC, 1985 p. 60).

Another effect is possible in a conceptual model in which fracture flow occurs in the unsaturated Topopah Spring welded unit under present conditions. Because the moisture flux is so much less than the saturated hydraulic conductivity of this unit, only the smallest-aperture fractures will be saturated. Alteration products might clog these fractures, diverting flow into larger ones. The effect would be an increase in velocity.

Sequences to be considered--The following sequences of events require further consideration:

17. Precipitation of zeolites or other minerals in the saturated zone reduces effective porosity without significantly improving the sorptive properties of the rocks.

18. Fracture flow occurs in the unsaturated zone at current percolation rates. Precipitation or alteration of minerals

blocks the small-aperture fractures and diverts the flow into larger fractures, increasing the water velocity.

2.1.13 Ground-Water Flow

Ground-water flow is expected to occur at the site and is part of the expected scenario. It is also part of all indirect-release sequences and therefore need not be treated separately.

2.1.14 Dissolution

Dissolution is not a concern at Yucca Mountain (EA, Section 6.3.1.6).

2.1.15 Brine Pockets

Brine pockets are found in salt beds under lithostatic pressure. Because of the substantial permeability of the tuffs at Yucca Mountain, the existence of substantial amounts of water of any composition under lithostatic pressure is not credible.

2.1.16 Orogeny

Within the Great Basin, mountains are being elevated. For Yucca Mountain the process of upthrusting involves movement of blocks along north-northeast trending faults that are generally downthrown to the west. The pattern has been in motion at least through the Quaternary (Swadley and Hoover, 1983, p. 7). Offset scarps of as much as 3 meters have been observed. The rate is less than 30 centimeters in 10,000 years (EA, Section 6.3.1.7.4).

While there is no suggestion of cessation or reversal of this process in the next 10,000 years, there is a possibility of changing rate. Evidence for possible rate variation comes from observations of areas in the Great Basin where uplift rates are as high as 4 (EA, Section 6.3.1.7.4) to 8 (NRC, 1985, p. 92) meters in 10,000 years.

With or without rate change, the effects of orogeny are experienced as faulting and erosion. These are discussed separately elsewhere.

2.1.17 Epeirogenic Uplift and Subsidence

Epeirogenic events could be of concern if the direction were uplift of the region. This might accelerate erosive processes. But the Great Basin physiographic province is essentially a graben. It is a subsiding block producing extension of the continental landmass. For most of the Cenozoic Era, it has been a collection basin for sediments eroding from bordering mountain ranges and plateaus. Such a process can reverse itself only very slowly, if at all. There is no suggestion that there might be a reversal in the next 10,000 years. Therefore, there is no likelihood of increased erosion due to epeirogenic uplift during that period.

Subsidence could be a problem if it brought the repository closer to the water table. However, the base level for the ground-water basin is not set by the ocean but by Death Valley and the Amargosa Desert, which are subsiding along with Yucca Mountain.

2.1.18 Isostatic Uplift and Subsidence

Isostatic movement is the regional response to glacial weight. The Great Basin province did not undergo Pleistocene glaciation. Renewed mountain glaciation on ranges bordering the province is not impossible during the next 10,000 years. But these would be essentially local mountains, and because these would be essentially local mountain glaciations, there should be no isostatic consequences.

2.1.19 Undetected Faults and Shear Zones

Likelihood of occurrence--Because of the extensive surface exposures of well-stratified bedrock at the repository site, it is unlikely that undiscovered major through-going faults in tuff exist there. Outside the repository site itself, undiscovered faults of considerable magnitude could be concealed by alluvium. In Paleozoic sediments or igneous intrusives below the tuff, undiscovered faults probably exist, but the expected flow path for contaminants does not go that deep, and so it is hard to see how such deep faults could have any significance for releases from the repository.

The existence of small undetected faults, of limited offset, in the southern half of the repository site is suggested by the geometry of structure sections (USGS, 1984, p. 51). Similar evidence indicates that such faults also exist southeast of the site, between Fran Ridge and Fortymile Wash (Scott and Bonk, 1984). Further evidence for the existence of as-yet-undetected minor faults is the discovery of fault zones not predicted by Scott and Bonk in Borehole G-4, in the northern portion of the repository block (NRC, 1985).

Indirect releases--The presence of small now-undetected faults in the repository block is taken for granted in the conceptual model of Montazer and Wilson (1984). One would expect that, in constructing the repository, efforts will be made to detect the wetter zones predicted by Montazer and Wilson below the intersection of these faults with the lower contact of the Tiva Canyon. (The wet zones would probably not coincide with the faults at repository depth unless the faults were vertical.) No waste would be emplaced in apparent wet zones, but it is conceivable that a wet zone would escape detection during repository construction and waste would be emplaced in it. The zone might be wet enough for moisture to move in fractures through the Topopah Spring welded unit.

Major faults might be pathways of preferential ground-water movement through the unsaturated zone. A major fault that intersected the repository workings would certainly be detected during the construction phase of the repository. A fault passing above the repository, but not intersecting it, would presumably divert moisture away and improve performance.

Below the repository, however, a major fault in the unsaturated zone might be significant. It could create a zone of higher permeability in the Calico Hills nonwelded unit. Percolating water might pass preferentially along the fault, with a higher velocity. In the worst case, the matrix in the fault might be saturated, leading to fracture flow.

Alternatively, matrix hydraulic conductivity could be reduced in a fault by formation of fault gouge. If the matrix hydraulic conductivity were reduced below the percolation rate, flow would be diverted into fractures.

Fault permeability might create a pathway for water movement from the water-table tuff aquifer down to an underlying carbonate aquifer. Contaminant velocities in the carbonate aquifer could be greater than in the tuff, because of greater hydraulic conductivity (Craig and Robison, 1984), greater hydraulic gradients, and perhaps less influence of matrix diffusion. (Matrix diffusion could be impeded if the carbonate rock has a lower matrix porosity than the tuff, if flow in it is concentrated in fractures of greater aperture, or if the fracture surfaces are coated with low-permeability material.) Movement from the tuff to the carbonate aquifer is only possible in the western portion of the repository site, because the head of the tuff aquifer in the eastern portion is less than that measured in the carbonate aquifer to the east of the site. It should be emphasized that existence of the carbonate aquifer beneath the repository site has not been confirmed, and it has been hypothesized that beneath the site, especially its western portion, the carbonate has been replaced by igneous intrusive rocks.

It is hard to imagine that an undetected fault in the saturated zone could perturb lateral flow in the tuff aquifer more than the flow barriers of unknown, and possibly fault-related, nature that have already been detected west and north of the repository block. Unless a great deal more is learned about these barriers, performance assessments of the "expected" scenario will have to include a sensitivity analysis to compensate for the limitations of our knowledge. This analysis should bound the effects of any undetected faults. Undetected faults affecting only the tuff aquifer therefore need not be considered separately.

Sequences to be considered--The following sequences require further consideration:

19. A wet zone below a minor fault through the Tiva Canyon lower contact escapes detection during repository construction and waste is emplaced in it. More water is available to degrade waste packages in this zone, and the flux through the zone is sufficient to cause flow in fractures.

20. An undetected major fault dips below the repository. The fault has greater permeability than surrounding unfaulted rock, and enhanced moisture flow is directed along it. As a result, water proceeding down from the repository passes through the Calico Hills nonwelded unit in fractures.

21. An undetected major fault dips below the repository. Because of the formation of fault gouge, matrix hydraulic conductivity in the fault is less than the moisture flux, and so moisture flows through the Calico Hills nonwelded unit along fracture in or just above the fault.

22. An undetected fault provides a path for water movement from the tuff aquifer beneath the western portion of the repository to an underlying carbonate aquifer. Contaminant movement is faster in the carbonate aquifer than in the tuff because of greater hydraulic conductivity and gradient. There is also less matrix diffusion in the carbonate than in the tuff.

2.1.20 Undetected Breccia Pipes

Because there are no soluble salt formations below the repository and no magmatic intrusions have occurred since the emplacement of the tuff, the existence of breccia pipes is not credible.

2.1.21 Undetected Lava Tubes

There is no evidence of volcanic activity at Yucca Mountain since the deposition of the Crater Flat and Paintbrush Tuffs more than 12 million years ago. The existence of any lava tubes in these units is therefore extremely unlikely.

2.1.22 Undetected Dikes

Likelihood of occurence--No intrusive dikes or sills have been detected in an extensive program of geologic mapping and drilling at Yucca Mountain (Scott and Bonk, 1984). The existence of such features is therefore very unlikely.

Indirect releases--A dike might provide a feature, of very low matrix permeability but high fracture permeability, cutting through nonwelded "capillary barriers" and providing a pathway for rapid water movement.

The hydraulic effects of a sill would be similar to those in a lava flow. The tuffs at Yucca Mountain are quite heterogenic and include several interbedded lava flows. Models of the hydrogeology of the site do not attempt to explicitly include such minor features. As features similar to sills are already implicitly included in the models, undetected sills do not have to be treated separately.

Sequences to be considered--The following sequence of events requires further consideration:

23. An undetected dike passing through the Calico Hills nonwelded unit beneath the repository has very low matrix permeability but fairly high fracture permeability. Moisture infiltrating along the dike therefore moves through fractures, and so travel times are small.

2.1.23 Undetected Gas or Brine Pockets

As discussed in Section 2.1.15, gas or brine pockets are not credible. The permeability of the tuffs on Yucca Mountain is such that any gas or brine pockets would long since have been drained.

2.1.24 Magmatic Intrusion

Likelihood of occurrence--Geologic relations suggest that the most likely type of magmatic activity at Yucca Mountain is basaltic volcanism rather than a plutonic intrusion (USGS, 1984). Because, as discussed in the next section, basaltic volcanism through the repository is at most barely credible, the possibility of plutonic intrusion need not be addressed.

Indirect releases--Intrusions could either reach the repository level itself or rise only to depths well below the repository where they affect water circulation. Each type of scenario will be discussed in turn.

It might be possible for a small amount of basaltic magma to rise toward the surface, intruding into the repository without erupting at the surface. The magma would form dikes or sills rather than large bodies (Crowe et al., 1982). Logan et al. (1982) analyze the thermal effects of emplacement of such dikes. In the absence of magmatic activity, the highest temperature the canisters would normally experience is approximately 250° C. Temperatures would rise above this only within about 10 meters of an intruding dike.

If repository drifts were left unfilled, magma rising through a vent might flow laterally into them and fill them. If canisters were emplaced vertically in the room floors, nearly all of them would encounter severe thermal stresses. Moisture in the magma would undoubtedly affect the waste canisters and cladding. This would be offset, however, by the emplacement of a flow barrier (with very small matrix hydraulic conductivity) above the waste canisters that would divert infiltration into the pillar areas of the repository.

These scenarios could undoubtedly be further elaborated. Magmatic intrusion into the repository seems unlikely at the Yucca Mountain site, however, in the absence of eruption. The indirect release mechanisms resulting from intrusion would almost certainly lead to smaller releases than the entrainment of waste magma that analyses of eruption scenarios have assumed. The risk of magmatic-intrusion scenarios will therefore be bounded, in both probability and consequences, by the risk of eruption scenarios, and so the intrusion scenarios need not be further analyzed.

Magmatic intrusions at depths well below the repository could create a system of hydrothermal ground-water circulation (NRC, 1985). However Crowe et al. (1982) indicate that the bodies of magma characteristic of magmatic activity in the region are not big enough to form the large-scale intrusions that are needed to create persistent hydrothermal circulation.

2.1.25 Extrusive Magmatic Activity

Likelihood of occurrence--The probability of volcanic disruption of a waste repository at Yucca Mountain has been calculated as between 1 in 3 billion and 1 in 20 million per year (USGS, 1984). The upper end of this range corresponds to a probability of 0.0005 of disruption during 10,000 years.

EPA regulations (EPA, 1985) place no restriction on releases of radioactivity with a probability of less than 0.001. However, in the guidance appended by EPA to the regulation, it is suggested that only events with a probability of less than 0.0001 can be ignored entirely. The thought behind this guidance would appear to be that if the probabilities of several events or processes that are capable of causing releases greater than allowed by the standard lie between 0.0001 and 0.001, these probabilities should be added together to see whether the total probability of such releases exceeds 0.001. In our view, arithmetic addition of probabilities in this manner would require much more precision in estimating the probabilities than is possible. Nevertheless, sequences involving extrusion of magma are included here for completeness.

Direct releases--Only waste that actually lies within a feeder dike or vent would be incorporated in the magma (Logan et al., 1982). Logan et al. assume that all waste in the physical volume of feeder dikes is so incorporated, but they point out that this assumption is probably conservative; usually very little country rock is observed in volcanic extrusive rocks.

The expected fate of waste incorporated in magma is described as follows by the USGS (1984):

> Waste incorporated in magmas would be dispersed by surface eruptions; the major pathway of contaminants would be through the pyroclastic component. Magma pathways can be approximated assuming that waste dispersal follows the dispersal patterns of lithic fragments studied in cone scoria. Thus, the greatest volume of dispersed waste would be in the scoria sheet, with lesser amounts dispersed with fine-grained (less than 65 micrometers) wind-born particles and in a scoria cone.

The principal pathways of human exposure from radioactivity released in this way would be direct exposure of individuals living in houses built of cinder-block made from the scoria, direct exposure of individuals living on the scoria, and inhalation of resuspended air-fall ash.

Indirect releases--Indirect releases from a volcanic eruption would be similar to those from a noneruptive intrusion. As discussed in the previous section, these may be neglected in comparison to the direct releases.

Sequences to be considered--The following sequence of events requires further consideration:

24. A basaltic volcano erupts through the repository. The volcano is fed through a dike; waste canisters within the dike mix with the magma, and their contents are erupted.

2.1.26 Meteorite Impact

The probability of a meteorite impact sufficient to breach a repository has been calculated by numerous authors (Koplik et al., 1982). Because of the probability of a given impact is largely independent of location and cratering depth depends only moderately on lithology, site-specific calculations are not necessary. However, the calculation does depend on the depth of the repository, because a lesser impact would be required to breach a 200-meter-deep repository at Yucca Mountain than one located at the depth of 600 meters, which most calculations assume.

KBS (1977, p. 104) gives the probability of a meteorite strike creating a crater 100 meters deep as 1 in 10 trillion per square kilometer per year. This would give the probability of occurrence within 10,000 years for a 6.15-square-kilometer repository as less than 1 in 100 million. This is far less than the probability cutoffs set by the EPA (1985), and no further consideration of the issue is required.

2.2 Human Activities

2.2.1 Shaft Seal Failure

Because free drainage of water around waste canisters is desirable in an unsaturated-zone repository, shafts and access ramps would not be sealed, except perhaps near the surface to prevent infiltration of runoff and entry by humans (Roseboom, 1983). Any runoff that did enter a shaft or ramp would quickly dissipate into the surrounding rock (Fernandez and Freshley, 1984). Shafts would, if necessary, be extended slightly below floor level of the repository to ensure drainage of any infiltrating water into the rock below. Failure of shaft seals is therefore not a consideration.

Sealing of the shaft may be required for nonhydrologic reasons (EA, Section 6.3.3.3.4; Fernandez and Freshley, 1984). However, because no credit is now taken for these seals in analyses of long-term performance, their failure does not require independent treatment.

2.2.2 Failure of Exploration-Borehole Seals

As with shafts, there is no need apparent at this time to seal exploration boreholes (Fernandez and Freshley, 1984), and therefore seal failure is not a consideration.

2.2.3 Faulty Waste Emplacement

Likelihood of occurrence--Waste emplacement carried out in deep mines will be hard to inspect and verify. Once a waste canister is in its final resting place, physical inspection would require taking it back out, so inspection of more than a small random sample of emplaced canisters is effectively impossible. As a result the potential for improper emplacement of some canisters is increased.

Improper manufacture of waste canisters will be limited by quality-control systems, but it is not possible to ensure perfection.

Direct releases--Any direct release of radioactivity due to improper waste emplacement would be considered an operational accident, and as such is outside the scope of this report.

Indirect releases--In the conceptual model of Montazer and Wilson (1984), the Topopah Spring welded unit contains wet zones, where the downward moisture flux is greater than elsewhere; these zones will be avoided when waste is emplaced. One or more canisters might nevertheless be placed in a wet zone by mistake. As it is not yet known how wet these zones will be, or how they will be detected, estimating the likelihood of such a mistake is not possible.

If drains are installed above waste canisters to divert water around them, some drains might be improperly constructed or omitted altogether.

Waste holes might not be drilled with the planned attitude. In the extreme case, waste canisters might be left lying flat on the floor of mine drifts rather than placed in drilled holes. Water would be able to drip on them even when their surface temperature is above 95° C, the approximate boiling point of water in the repository. The canisters would also have a larger cross section to intercept downward-moving moisture.

Canisters might be placed closer together than specified, causing them to reach a higher temperature than predicted. Higher fuel temperatures would accelerate cladding corrosion (Gause and Soo, 1985).

Waste canisters might be improperly manufactured, or they might be abraded or punctured during emplacement.

Sequences to be considered--The following sequences require further consideration:

25. Canisters are placed by mistake in wet zones. These canisters are exposed to more water than planned and the water moves more quickly to the water table.

26. Drains installed to divert water around canisters are improperly built or omitted altogether over some canisters. As a result, more water is available to corrode canisters and dissolve the spent fuel.

27. Canisters are left lying on the floor of repository drifts. These canisters have poorer heat removal than those properly emplaced, and their increased horizontal cross section raises the amount of water they intercept. The additional water and higher fuel temperature accelerate canister and cladding corrosion. The manner of emplacement allows water to drip on the canisters and corrode them even while their temperatures are well above 95° C.

28. Canisters are placed closer together than planned. As a result, temperatures inside the packages are higher than anticipated. Corrosion of fuel cladding is accelerated as a consequence.

29. Some waste canisters are manufactured so improperly that they fail early.

30. Some waste canisters are punctured or abraded during emplacement.

2.2.4 Irrigation

This section discusses the effects of applying irrigation water at the surface, without reference to the source of the water. Effects of withdrawing irrigation water through wells located in or near the repository are discussed in Section 2.2.6, which discusses ground-water withdrawal.

Likelihood of occurrence--Irrigation directly over the repository seems extremely unlikely, given the planned institutional controls, great depth to the water table, absence of nearby surface water, rough topography, and poor soils. This possibility seems not to warrant detailed consideration.

Irrigation in the flats on either side of Yucca Mountain is somewhat less improbable, because of the flatter topography and lesser, although still considerable, depth to water. Nevertheless, soil quality is probably poor (judging from the coarse-grained nature of the sediments in the valleys; further study of this point might be useful) and contained institutional controls or at least site markings would tend to direct agricultural projects away from Crater and Jackass Flats toward the Amargosa Desert.

Indirect releases--Irrigation water applied to the surface near the repository could move laterally into areas of dryer rock and thus increase the moisture flux through the repository. Midway Valley (see Figure 2), which is the nearest area to the repository topographically suitable for irrigation, is about 1 kilometer from the site boundary. The floor of Midway Valley lies no more than 200 meters above the proposed repository level. As the suction in the Topopah Spring tuff in the repository block seems to be on the order of 10 to 100 bars, or 100 to 1000 meters (Montazer and Wilson, 1985), the gradient driving unsaturated flow toward the repository would be on the order of unity, or somewhat less. This is close to the downward gravitational potential gradient of 1, and because the tuff is stratified, hydraulic conductivity is likely to be greater in the horizontal than in the vertical direction (Freeze and Cherry, 1979, pp. 32-34). It is therefore not impossible that irrigation water applied in Midway Valley could infiltrate through the repository.

Irrigation might also raise water tables and thus change the ground-water velocity in the saturated zone. But irrigation south or east of Yucca Mountain could only reduce the gradient at the mountain, further isolating the repository. Higher water levels upgradient, to the east or northeast, would have little effect, because flow barriers separate those areas from the main part of the repository site. The head drops across those barriers (45 meters to the west, and 300 meters to the north) exceed any changes in water level that could reasonably be expected from irrigation.

Sequences to be considered--The following sequence of events requires further consideration:

31. Irrigation in Midway Valley increases the moisture flux through the repository.

2.2.5 Reservoirs

Given the highly ephemeral nature of all streams in the vicinity of Yucca Mountain, the construction of large reservoirs is not credible. Any small impoundments that might be built to collect runoff, to be worthwhile, would have to be lined, and therefore would not affect the subsurface.

2.2.6 Intentional Ground-Water Recharge or Withdrawal

Hydraulic effects of ground-water recharge and withdrawal are discussed in this section. Direct removal of waste when wells are drilled is discussed in Section 2.2.11.

Likelihood of occurrence--Artificial recharge would be employed to enhance ground-water supply. A source of water is required; this source may be distant or local. If the source is distant, users would probably find some sort of aqueduct system to be less expensive than a process of infiltrating the water through hundreds of meters of rock to the water table, waiting years for increased ground-water flow, and pumping the water back up to the surface. Local water sources are limited to intermittent runoff. Such runoff could be trapped in covered cisterns in order to increase recharge. This technique was used in the ancient Middle East.

Withdrawal of local ground water for purposes of irrigation or domestic supply is more reasonable than importation of water from distant sources. The extent of water withdrawal will reflect the durability of institutional controls and markers, the size of the local population, and the economic and social arrangements of future civilizations. The limited information we have suggests that soils near Yucca Mountain may drain too rapidly to support the sustained agricultural community using current practices, but more information about soil conditions in Crater Flat, Midway Valley, and Jackass Flats is needed to refine this prognosis. If a significant population center develops in the area, the most likely site for wells is along Fortymile Wash where Topopah Spring welded tuff is below the water table. This is where the current supply wells J-12 and J-13 are located.

If mines are developed below the water table at Yucca Mountain, dewatering will be required. As discussed in Sections 2.2.11 and 2.2.13, such mining is unlikely but not impossible.

Indirect releases--Artificially intensified recharge could lead to a larger moisture flux through the repository.

Artificial withdrawal of water, depending on where it takes place, could reduce the distance to the accessible environment. It would also tend to increase gradients and, therefore, ground-water velocities in the saturated zone adjacent to the wells. On the other hand, the path length in the unsaturated zone would be increased to the extent the water level is lowered.

Sequences to be considered--The following sequences require further consideration:

32. Water is collected in covered cisterns above the repository to enhance ground-water recharge. The moisture flux through the repository is therefore increased, especially beneath the cisterns.

33. Irrigation wells are drilled in Midway Valley, reducing the distance to the accessible environment and increasing the hydraulic gradients in the saturated zone beneath the repository.

34. Irrigation wells are drilled in Crater Flat or Jackass Flats, increasing the hydraulic gradient between the repository and the accessible environment.

35. Pumping rates increase in the presently irrigated area around the town of Amargosa Valley (formerly Lathrop Wells). The water table is significantly drawn down, and the hydraulic gradient between the repository and the accessible environment is increased.

36. Mine dewatering is carried out directly below the repository. The saturated zone is eliminated as a barrier, but the depth of the unsaturated zone increases.

2.2.7 Chemical Liquid Waste Disposal

Future practices in waste disposal cannot be predicted with certainty, but current practices suggest that Yucca Mountain is a very unlikely location for disposal of liquid chemical wastes. Chemical wastes are generally disposed of as liquids in two ways: deep-well injection and surface impoundments.

Deep-well injection generally is into deep, highly saline sedimentary aquifers from which little discharge is anticipated. A deep sedimentary aquifer does exist, if not under the mountain at least immediately to the east; but the water in it is fresh. Furthermore, the aquifer is so far below the repository that injection would have no effect on the repository. If hydraulic gradients were to be altered in aquifers near the water table, the repository would be indirectly affected. But avoiding disturbance of water table aquifers is normally a criterion for choosing sites for deep-well injection.

The rugged terrain of the repository site would be an unlikely location for a surface impoundment for waste disposal. An impoundment in one of the flats near the repository would have an effect similar to irrigation, and its effects would resemble those of irrigation.

The current trend in waste disposal is, for environmental reasons that are unlikely to change, away from surface impoundments and deep-well injection. This trend further reduces the likelihood that such activities will affect a waste repository.

2.2.8 Large-Scale Alterations of Hydrology

Likelihood of occurrence--A large-scale alteration of the hydrology of the region by human activity would most likely be related to introduction of an active management regime for the Alkali Flat-Furnace Creek Ranch ground-water basin. If sufficient demand for water develops in the area, the motivation for such a scheme would exist, because one could capture fresh water that now discharges unused by evapotranspiration in Alkali Flat.

Another possible cause of large-scale alteration of the hydrologic regime is the damming of the Colorado River. Because Yucca Mountain is well above the level of the Colorado and no other major water sources are available in the region, major water projects are unlikely to affect a future repository (Hunter et al., 1982, p. 118).

Indirect releases--Active management would tend to change, and more likely than not increase, hydraulic gradients under Yucca Mountain. The tendency for gradients to increase would occur because the recharge areas are to the north of Yucca Mountain and the most likely areas of use are to the south and west. The purpose of active management would probably be to increase recharge in the north and withdrawals in the southwest. More water would have to flow under Yucca Mountain, and so gradients would be increased.

Sequences to be considered--The following sequence of events requires further consideration:

37. An active management scheme is introduced for the Alkali Flat-Furnace Creek Ranch ground-water basin, by which hydraulic gradients in the saturated zone beneath the repository are increased.

2.2.9 Undiscovered Boreholes

Likelihood of occurrence--Yucca Mountain is not particularly attractive as a target of mineral exploration and is entirely unattractive as a petroleum prospect. The primary period of exploration in the area before strict Federal control was established in the 1950s was 1905-1910, before deep drilling was widely used for metal prospecting (Bell and Larson, 1982). Extensive exploration and records searches have produced no evidence of deep boring or excavation. It is therefore probable that no undiscovered boreholes exist (EA, Sections 6.3.1.8.4 and 6.3.1.8.5).

Indirect releases--Undiscovered, unsealed boreholes reaching to or below the repository level would promote free drainage and therefore would improve repository performance unless waste canisters were emplaced within the borehole. If waste were emplaced in tunnel floors, placement of canisters within old boreholes would be extremely unlikely, because the boreholes would be discovered during tunnel construction. A problem could arise if wastes are placed in horizontal holes between drifts. Then discovery of old boreholes would be less certain. A waste canister placed in an old borehole might encounter unusually wet conditions if current or future moisture fluxes were sufficiently large.

Sequence to be considered--The following sequence requires further consideration:

38. A horizontally emplaced waste canister lies in the trace of an old, undiscovered borehole. Moisture conditions are wetter than predicted by Montazer and Wilson (1984), either because of current conditions different from those they describe or

because of climate change. Consequently, water flows in fractures in the old borehole, and the canister is wetted more than other canisters.

2.2.10 Undiscovered Mine Shafts

Likelihood of occurrence--The review of records and exploration described in the previous section strongly indicates that no undiscovered deep mine shafts exist on Yucca Mountain. However, shallow prospects may exist.

Indirect releases--An old prospect in the bed of one of the washes, filled with rubble, might retain water after floods and therefore be a location for enhanced infiltration.

Sequences to be considered--The following sequence of events requires further consideration:

39. An old prospect in a wash retains water after floods and therefore is a source of enhanced infiltration. The wet zone beneath it is not detected during repository construction, and waste is emplaced in it.

2.2.11 Exploratory Drilling

Likelihood of occurrence--There is no evidence for the existence of energy resources other than low-temperature geothermal energy on Yucca Mountain or its vicinity, and the area is not geologically favorable for their occurrence. Other minerals (gold, cinnabar, fluorite) are mined at Bare Mountain, about 10 miles to the west, and have been mined at locations some tens of miles to the east of Yucca Mountain, now part of the Nevada Test Site. However, there are no published reports of commercial-grade mineral resources being found in the repository drilling program. Therefore, Yucca Mountain is a relatively unattractive target for exploratory drilling for natural resources (Bell and Larson, 1982; EA, Section 3.2.4).

Fresh water underlies Yucca Mountain. Water is also available from a more productive aquifer at lesser depth under Fortymile Wash a few miles to the east; future water users would be likely to follow current practice and get their water there. Nevertheless, the possibility of drilling water wells at Yucca Mountain cannot be ruled out.

After centuries of cooling and radioactive decay, spent nuclear fuel might be an attractive resource. Chemical processing might extract valuable amounts of uranium, plutonium, rare fission-product elements, zirconium, and perhaps copper, lead, or other canister components. Certainly, the mineral values of the spent fuel far exceed any minor natural resources that might be present at Yucca Mountain.

If records showing the exact location and layout of the repository had been lost, exploratory drilling might be undertaken to prepare for recovery of the spent fuel. Those undertaking such drilling would presumably take appropriate precautions against the consequences of drilling into the waste. Waste-recovery operations themselves are discussed below in Section 2.2.15.

Some authors have estimated the probability of exploratory drilling through a waste repository. The most recent such calculation, by Smith et al. (1982), is the first to address disposal media other than salt, but it simply takes a probability for salt, based on the likelihood that the existence of the repository will be forgotten rather than the intrinsic attraction of the repository site as an exploration target, and multiplies it by an arbitrary correction factor. This estimate is therefore of no value in assessing the site-specific likelihood of drilling at Yucca Mountain.

Another consideration in determining the probability of exploratory drilling through a waste repository is the location of Yucca Mountain near the Nevada Test Site. The persistence of surface radioactivity in localized regions may result in long-term administrative restriction of the area, and test craters will serve as markers indicating the special uses to which the area has been put.

Direct releases--If a borehole were drilled through a waste canister, waste would be brought to the surface with the cuttings.

Indirect releases--Water introduced with drilling mud would increase the moisture content of rocks near a borehole. The moisture would infiltrate through the system, temporarily increasing the flux in the vicinity.

An unsealed borehole might create a pathway for flow through the Paintbrush nonwelded unit. The Topopah Spring welded unit would be wetter in the region directly below.

Drilling fluids often contain surfactants. Surfactants shift the characteristic curve of an unsaturated medium in the direction of lower water content at the same tension, or smaller suction at the same water content. As a result, the smaller pores in the region immediately around the borehole might drain. Air rather than water might to some extent become the wetting phase. During subsequent episodes of infiltration, the air in the small pores might drain slowly and thereby force the water to flow through larger pores and fractures.

Sequences to be considered--The following sequences require further consideration:

40. Exploratory drillers intercept a waste canister and bring waste up with the cuttings.

41. Water introduced into the unsaturated zone as drilling fluid by exploratory drillers drains downward, through the repository.

42. An exploratory borehole creates a pathway for preferential flow through the upper nonwelded unit, and a wetter zone develops beneath in the Topopah Spring welded unit.

43. Surfactants introduced into unsaturated rock by drilling fluids shift its characteristic curve, draining smaller pores around

the borehole. Water introduced by subsequent infiltration events acts as though air were the wetting phase, and flows through large pores and fractures.

2.2.12 Archaeological Exhumation

Given the markings and recordkeeping that will be carried out at a repository, archaeologists planning to excavate a repository are likely to know what lies below before starting. Even without records and markers, excavation of the surface facilities would probably reveal that radioactivity had been handled at the site. Below the surface, the design of the mine (such as the low extraction ratio and the lack of correlation between the mine layout and any potentially ore-bearing geological feature) would immediately suggest that this was a waste-disposal facility and not a mine. An archaeologist excavating old mines should be familiar with "ancient" mining practices and should easily interpret these signs. In any case, removal of waste from a repository by future archaeologists is not a proper concern of performance assessment.

2.2.13 Resource Mining

Hydraulic effects of water withdrawal are discussed in Section 2.2.6. Any lowering of the water table due to "mining" of ground water or mine dewatering would enlarge the unsaturated zone and so have a favorable effect on waste isolation. The discussion here will therefore be limited to effects of mining on the unsaturated zone.

Likelihood of occurrence--As discussed in Section 2.2.11, the resource potential of Yucca Mountain is fairly small, and institutional controls and markers are likely to discourage future mining activity. The likelihood of future mining for minerals other than the waste itself is therefore small, but mining of Yucca Mountain is not impossible.

The repository horizon in particular will be explored with extreme thoroughness for any mineral resources by the very act of building the repository. If deposits are discovered during the construction of the repository, either they will be extracted or the repository will be moved elsewhere. Furthermore, anyone encountering waste canisters in the subsurface will be able to recognize their anthropogenic origin. Therefore, scenarios in which the repository level itself is mined for other minerals are not credible.

Direct releases--A shaft excavated for a mine below the repository horizon might be drilled through one or more waste canisters.

Indirect releases--A mine shaft could have the same effects as an exploration borehole, discussed in Section 2.2.11.

Sequences to be considered--The following sequences require further consideration:

44. Builders of a mine shaft intercept a waste canister, and bring radioactive waste up with the mine waste.

45. Water introduced into the unsaturated zone for mining above the repository drains downward, through the repository.

46. A mine shaft creates a pathway for preferential flow through the upper nonwelded unit, and a wetter zone develops beneath in the Topopah Spring welded unit.

47. Surfactants introduced into unsaturated rock by drilling fluids shift its characteristic curve, draining smaller pores around the mine. Water introduced by subsequent infiltration events acts as though air were the wetting phase and flows through large pores and fractures.

2.2.14 War

Disruption of a repository 200 meters below the surface by war would require a nuclear explosion, and a large one at that. In an unsaturated-zone repository, fracturing of the rock would not in itself affect isolation; actual exhumation of the rock is required. This would require a direct hit by a bomb larger than any weapon known to be in stockpiles (Hunter et al., 1982, p. 117). The release of waste from a repository would be a minor consideration in a war in which such bombs were exploding.

2.2.15 Sabotage

After a few hundred years of institutional control, spent fuel is less toxic than such easily obtained substances as selenium, cyanide, mercury, and arsenic (Koplik et al., 1982). This comparison is based on acute toxicity, which is the relevant factor for sabotage. The spent fuel will be buried at great depth, and be recoverable only at considerable trouble and expense. It is hard to imagine that the lengthy and difficult operations required for waste recovery would escape the attention of the authorities. Recovery of waste from a repository would therefore be quite an unattractive course of action for an aspiring saboteur.

2.2.16 Waste Recovery

The resource values in spent fuel are such that recovery at some future time might well be attractive. However, permanent disposal has been chosen as a national policy, and it would be inconsistent to base burial plans on an expectation of recovery. If we think that future generations might choose to recover the wastes, we should make their job easier and safer, not more difficult. If performance assessments that include waste recovery scenarios are used to pick a repository site and design for maximum retention of waste, the tendency would be to choose the site from which recovery is most difficult.

In any case, individuals undertaking to recover wastes from a repository would be deliberately taking the risks involved on themselves.

Waste-recovery scenarios are therefore not an appropriate subject of long-term performance assessments. (Operational safety during the period of planned retrievability is, of course, a matter of concern in analyzing preclosure performance.)

2.2.17 Climate Control

Likelihood of occurrence--A large, widespread increase in precipitation, especially one that would increase recharge beyond the levels expected for future pluvial periods (see Section 2.1.1), is far beyond current technology. But it is not unreasonable to anticipate that future civilizations might use artificial methods of climate modification to increase precipitation in southern Nevada, including the Yucca Mountain area.

Whether speculation on future technological developments is an appropriate part of performance assessment is questionable. The Environmental Protection Agency standards (EPA, 1985) do not seem to make any exception for such scenarios, so they will be described here.

Indirect releases--As discussed in Section 2.1.1, the primary way in which climatic change, whether natural or artificial, could affect repository performance is by changing the rate of ground-water recharge. The scenarios are similar whether the cause of the increased recharge is natural or artificial, except that in the case of artificial climate change one cannot assume that future recharge levels will remain below past levels.

Sequences to be considered--The following sequences require further consideration:

48. An increase in recharge at the repository site due to artificial climate change increases the unsaturated water flux through the repository. This reduces canister lifetimes, increases waste dissolution rates, and, by causing fracture

flow in the welded Topopah Spring unit, increases contaminant velocity in the unsaturated zone.

49. An increase in recharge due to climate modification raises the water table beneath the repository above the top of the Calico Hills nonwelded tuff unit. Also, fracture flow is induced in the welded Topopah Spring unit, so that contaminant travel times to the water table are drastically reduced.

50. Recharge induced by large-scale climate modification raises the regional water table sufficiently to flood the repository, accelerating waste-package failure and creating a pathway for rapid flow to the accessible environment through the highly conductive welded Topopah Spring tuff. With the higher water table come discharge points closer to the repository, reducing the distance to the accessible environment. (As with sequence 4, the ramifications of this sequence will not be developed further in the belief that it will be shown not to be credible.)

51. A higher water table due to climate modification short-circuits a flow barrier in the saturated zone, changing the pattern of flow.

52. Perched water develops above the repository because of climate-modification-induced recharge, diverting downward flow through the repository into localized zones. Some waste canisters are wetted more than others, affecting canister lifetimes and leach rates.

53. An increase in recharge due to climate control causes perched water to develop at the base of the Topopah Spring welded unit. Flow through the Calico Hills nonwelded unit is diverted into fracture zones draining the perched water table.

2.3 Waste and Repository Effects

The construction and use of a repository will impose thermal, mechanical, chemical, and radiological stresses on the rock around it. All of these processes can interact, and so waste- and repository-induced failure sequences are hard to enumerate and classify. In the discussion below, which is based on the IAEA list of relevant processes and events, a sequence is generally listed under the phenomenon that plays the most important role in it. The classification is necessarily arbitrary at some points.

Useful descriptions of the role that might be played by coupled processes in the performance of a waste repository are given by Tsang and Mangold (1984) and de Marsily (1985).

2.3.1. Differential Elastic Response to Heating

Likelihood of occurrence--Because both temperature and lithology will vary from place to place in a repository, differential thermal expansion will occur.

Indirect releases--Thermal expansion of rocks might cause fractures either to open or to close. This would be of little consequence under current natural moisture flux conditions, where all flux is believed to flow through the matrix.

In conditions of enhanced flux caused by heating, however, closing of fractures could tend to prevent drainage and increase the accumulation of condensate above the repository. Effects of such condensate are discussed in Section 2.3.4.

If there is fracture flow under natural conditions, closing of fractures could divert flow into larger-aperture fractures, increasing the velocity of percolation.

A consequence of thermally driven rock movements may be some opening of joints within perhaps 20 to 30 meters of the surface (Johnstone et al., 1984). This might increase the permeability of the Paintbrush nonwelded unit and create local zones of enhanced infiltration through it where the geometry of the layers is appropriate.

Differential expansion of rocks around a waste canister might place stresses on the canister, possibly enhancing the chances of stress-corrosion cracking. At the extreme limit, canisters would be sheared by imposed stresses.

<u>Sequences to be considered</u>--The following sequences require further consideration:

54. Thermal expansion closes most fractures near the repository. Pre-existing fracture percolation is diverted into fractures of larger aperture, increasing water velocity.

55. Differential thermal expansion of surrounding rocks stresses canisters, leading to stress corrosion cracking.

56. Differential thermal expansion of surrounding rocks creates stresses that shear canisters.

57. Rock movements driven by thermal expansion of underlying units open fractures through the Paintbrush nonwelded unit. This creates local zones of increased flux through the unsaturated units below.

2.3.2 Nonelastic Response to Heating

<u>Likelihood of occurrence</u>--The primary nonelastic response to thermally induced stresses on rocks is fracturing. Calculations (EA, Section 6.3.1.3.4) indicate that no fracturing is expected under expected heat loadings, but a heat loading 10 percent higher would cause

fracturing within 10 centimeters of waste canisters. Such fracturing would be created by the mechanical stresses imposed by the combination of the excavated opening and thermal expansion. Thus, fracturing of this type must be considered possible.

The same forces, but with the thermal stresses playing a relatively lesser role, could also fracture rock immediately around drifts. Such fracturing is discussed in Section 2.3.6.

Indirect releases--In general, free drainage in the Topopah Spring welded unit is considered a positive condition for the repository, and therefore thermal fracturing would not be an adverse condition. There are already sufficient fractures in the unit, viewed in bulk, to transmit a flux far in excess of the current one, no matter what reasonable hypothesis one holds about the nature of flow in the Yucca Mountain unsaturated zone. The effect of additional fracturing on the bulk rock would simply be to increase the amount of void space in the fractures, which has no effect on travel times.

New fractures around waste canisters would not contain any fracture-filling minerals and might therefore act as capillary barriers to flow through the matrix. Movement across the fractures would most likely be localized at those points where the two faces of the fracture contact. In a fracture newly created by an active stress field, contact points could be very few, perhaps leading to formation of water droplets or film flow on the canisters. This could hypothetically accelerate corrosion and waste dissolution, by increasing the amount of moisture contacting the canister and by creating inhomogeneities that could serve as sites for localized corrosion.

Sequences to be considered--The following sequence of events requires further consideration:

58. Thermally induced fracturing of rocks immediately surrounding waste canisters creates capillary barriers to movement of

moisture between blocks of the rock matrix. The matrix is locally saturated, forcing flow out into the fractures and resulting in film flow or droplet impact on waste packages. The result is accelerated localized corrosion and waste dissolution.

2.3.3 Temperature Effects on Fluid Properties

Repository temperatures are certain to affect fluid behavior, principally by shifting the moisture characteristic curve and increasing the humidity of air in equilibrium with moisture at a given tension. This will cause temperature-driven movements of water, in comparison with which the effects of temperature on such fluid properties as pressure, density, and viscosity and on rock properties such as relative permeability will be minor. Therefore changes in these fluid properties are subsumed within the fluid-migration sequences presented in the next section.

2.3.4 Temperature-Driven Fluid Migration

<u>Likelihood of occurrence</u>--When temperatures in an unsaturated-zone repository are elevated, thermal forces will largely control the movement of moisture near the repository workings.

The expected mechanism is as follows: At higher temperatures, water vapor pressures in equilibrium with a given moisture suction will be greatly elevated. Consequently, initial heating of rock around the repository will cause evaporation of some water in the pores, leading to higher vapor pressure, lower liquid saturation, and higher suction (that is, more negative potential). Temperature, vapor-pressure, and suction-head gradients, such as those shown schematically in Figure 6, could be created; these gradients will lead to diffusion of vapor away from the canisters and suction-driven flow of liquid towards them. Water will flow toward the canisters in the liquid phase, evaporate as it enters a region of higher temperature, diffuse away, and condense to repeat the cycle. The extent of this "heat-pipe" effect will depend on the flow

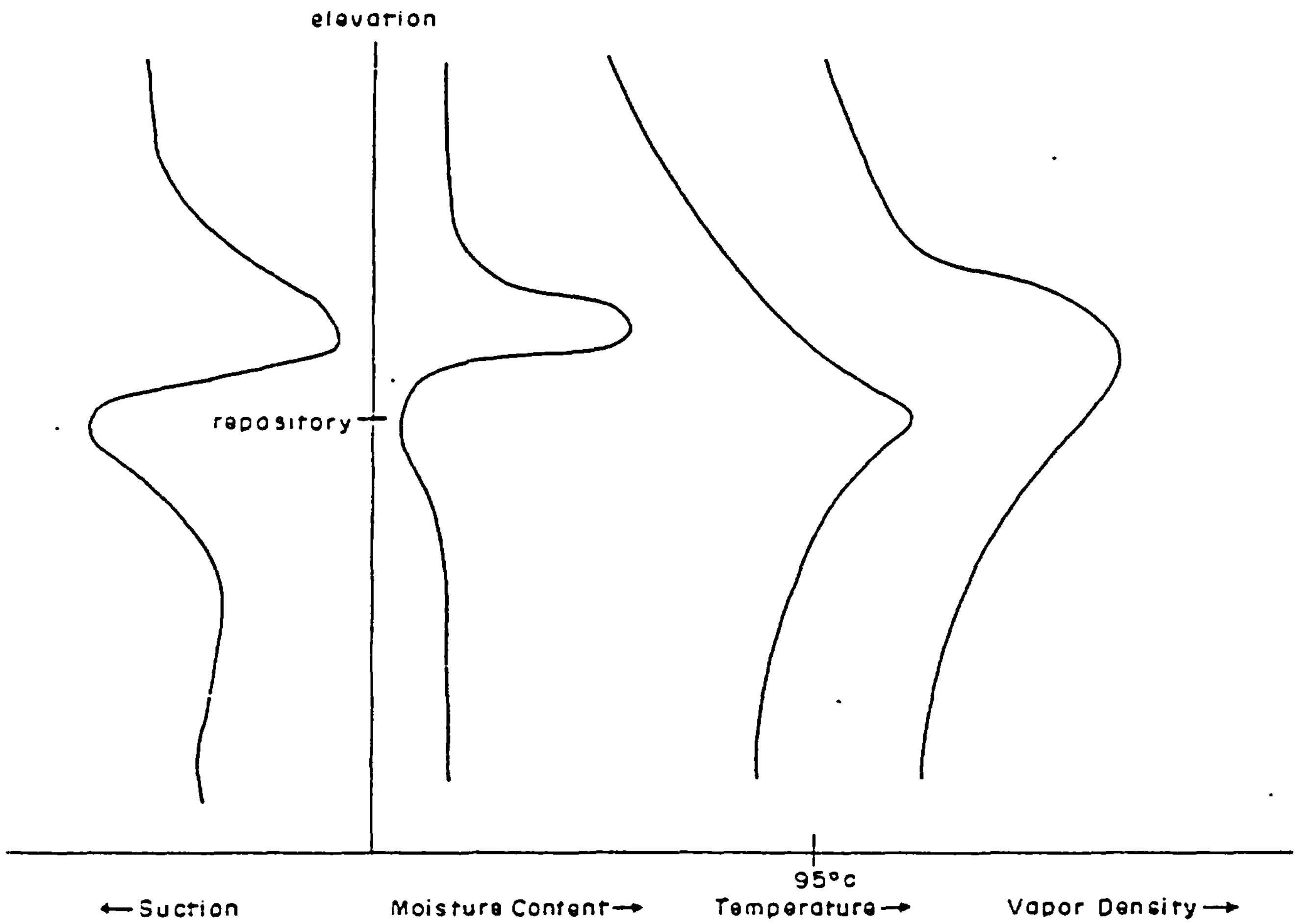

Figure 6. Conceptual illustration of the variation of thermodynamic variables with depth when the repository is heated above 95°C.

characteristics of the tuff matrix and fractures in the thermally perturbed environment. Because of the shape of the repository, the dominant flows will be vertical except near the repository margins.

Any net infiltration will continually add water at the top of this system. It is not clear whether the rate of water removal from the bottom of the system will exceed or be less than the rate of addition.

Temperature inhomogeneities will exist within the repository because of variations in density of waste emplacement, waste age, and fuel burnup. This could cause lateral movement of moisture, leading to the existence of relatively wet zones.

The heating of the water in the saturated zone beneath the repository could cause convective water movement.

<u>Direct releases</u>--If sufficient water accumulates in this two-phase convection system, a saturated zone could be created in the area of condensation. If vapor were unable to move away laterally, the gas phase beneath this saturated region would build up a vapor pressure exceeding atmospheric, with the head of steam equal to the thickness of the water "cap." If a sufficient steam pressure accumulates, and there is a pathway for it to move rapidly upward, it might be released at the surface as an artificial geyser.

Even leaving aside the extreme improbability of satisfying all the assumptions required by this scenario, it would not lead to release of any radioactivity. Near the repository, the direction of liquid movement is only toward the waste. Since the wastes are soluble only in liquid water and not in vapor, no wastes (aside from the minor amounts of gas present) can move away from the canister. Consequently, the geyser would not be contaminated.

A less extreme mechanism for release is the formation of aerosols due to vigorous boiling of water near a hot canister (Tsang and Mangold,

1984) and transport of these aerosols, with dissolved radioelements, to the surface. This sequence requires the water droplets to pass through 200 meters of fractured porous medium--which will act as a filter--without colliding with a solid surface. It does not seem credible. At most, contamination could be carried a short distance above the waste before adhering to a rock surface. As liquid water in rocks above the waste will be moving downward, the dissolved radioelements would then move downward.

Indirect releases--A number of mechanisms can be imagined whereby the thermally driven moisture movements around an unsaturated repository would indirectly enhance releases of radioactivity. Among them are numerous ways in which two-phase water recirculation could lead to plugging of pores and consequent fracture flow. The pore-plugging mechanisms all involve chemical reactions of some sort and consequently are discussed in Section 2.3.10.

Alternatively, if a significant amount of water were to accumulate above the repository during the thermal period, the downward flow of this water after the thermal period ended might be sufficient to saturate the rock matrix and cause flow in fractures.

Temperature inhomogeneities could cause localized accumulation of moisture above the repository. Wet zones might exist below these moisture accumulations, perhaps for a considerable time.

Another possibility, especially if bare canisters are emplaced in the floors of repository drifts, is that a major temperature difference will develop across a room or other air gap above a canister. Moisture would condense on the roof and drip onto the floor, where it would boil or rapidly evaporate. If water were to drip onto hot canisters in this way, corrosion might be significantly accelerated.

It has been suggested (Tsang and Mangold, 1984) that the Soret effect or thermal osmosis could be an important driving force for radionuclide movement around waste canisters. However, these effects are primarily of interest for their effects on clay buffer material around canisters. No clay buffers are included outside the canisters in the tentative Yucca Mountain package designs (Gregg and O'Neal, 1983). In any case, the role of these mechanisms is to redistribute solutes within a volume of fluid. As dissolving species move away from the vicinity of the solid phase, dissolution is accelerated. As long as calculations of waste dissolution assume that the small amounts of water contacting canisters form completely saturated solutions, any possible effects from these phenomena will be bounded by the results.

In the saturated zone, thermal convection could cause water to rise at the repository site and flow outward in the uppermost portion of the tuff aquifer. This could increase ground-water velocity.

Sequences to be considered--The following sequences require further consideration:

59. Water accumulates above a repository during the thermal period because of the "thermal barrier" created by evaporation and condensation. When gravity-driven flow resumes, a large volume of water contacts canisters, and flow in the Topopah Spring unit, and possibly the Calico Hills unit, goes through fractures.

60. Emplacement of waste in the floor of repository drifts creates a large thermal gradient across the drifts. Moisture condenses on the roof and drips onto canisters, accelerating corrosion.

61. Temperature inhomogeneities in the repository lead to localized accumulation of moisture above it. Wet zones form below the areas of moisture accumulation. In the wet zones, water velocity is increased, and more water contacts waste packages.

62. A thermal convection cell arises in the saturated zone beneath the repository. The thermally driven outward water flow in the upper portion of the tuff aquifer increases ground-water velocities.

2.3.5 Canister Movement

The welded Topopah Spring tuff does not flow or strain elastically to more than 1 percent deformation (EA, Section 6.3.1.3.3). Therefore, significant canister movement is not expected as a result of thermal stress.

2.3.6 Local Mechanical Fracturing

Likelihood of occurrence--The EA (Section 6.3.3.2.4) suggests that there is a possibility of fracturing at the periphery of drifts. The mechanical stresses imposed by the combination of the mined opening and thermal expansion would cause this fracturing. Mechanical stresses induced by high gas pressures in the rock matrix resulting from rapid vaporization of liquid water very near the waste package might also potentially cause fracturing.

The same forces, with the thermal expansion playing a relatively greater role, could also fracture rock immediately around waste canisters; such fracturing is discussed in Section 2.3.2.

Hunter et al. (1983, pp. 70-76) suggest that subsidence into the void space of a repository located in the Topopah Spring welded tuff unit could create open fractures extending to the surface. The long-term mechanical calculations described by Johnstone et al. (1984) show that no fracturing at all will occur between the points 30 meters below the surface and 30 meters above the repository. However, Johnstone et al. assumed a particular thermal loading that may not correspond to the final areal power density used in the repository. It does not appear that the suggestion of Hunter et al. is credible, but it is suggested that bounding calculations be performed for completeness to confirm that subsidence has no significant effect at this site.

Indirect releases--Fracturing would increase the permeability of the tuff. Because free drainage is a positive factor in the repository horizon, and any fractures of this type would adjoin the far-more-transmissive unsealed repository drifts, the increases in permeability would not lead to increased releases of radioactivity.

Fracturing might also lead to rock falls or rockbursts. If rocks were to fall or burst from the roof or wall of a drift and strike a canister, the canister might be punctured.

Sequences to be considered--The following sequence requires further consideration:

63. Rockbursts propel rocks into waste packages and puncture the canisters.

2.3.7 Corrosion

Likelihood of occurrence--Dayal et al. (1982) define and describe various corrosion mechanisms; readers should refer to that report for background information. McCright et al. (1983) describe potential corrosion mechanisms for canisters in an unsaturated repository at Yucca Mountain.

Current estimates of canister lifetime are based on uniform corrosion (Sinnock et al., 1984). Uniform wet corrosion may be expected on any parts of the canister that are exposed to liquid water. Dry corrosion will occur on the canister where it is exposed to air.

The potential for nonuniform corrosion of canisters at Yucca Mountain has not yet been fully evaluated (EA, Section 6.4.2.2), but it is such corrosion that is of concern in evaluating the potential for canister failure. Two general classes of corrosion are possible for the canister materials under consideration at Yucca Mountain: corrosion accelerated by sensitization of the metal, and corrosion promoted by high-ionic-strength waters.

Canister metals could be sensitized by heating at elevated temperatures over long periods of time in the repository.

Although the waters of the repository horizon are generally of low salinity, water dripping onto a hot canister could evaporate, leading to a buildup of various ions at corrosion sites. Corrosion by mechanisms requiring various promoter ions could ensue, even though the natural waters would not be corrosive.

NRC (1985, p. 105) argues that there is a strong potential for stress-corrosion cracking of the currently preferred canister material, Type 304L stainless steel, and that other types of localized corrosion cannot be ruled out. Scenarios involving such corrosion mechanisms must be considered possible at this time.

Gause and Soo (1985) have reviewed potential corrosion mechanisms for fuel cladding. The fuel cladding is made of Zircaloy, except for less than 1 percent of the fuel elements, which are clad in steel. Cladding may under expected conditions corrode from the inside out, and high temperatures would accelerate this internal corrosion. Temperature-accelerated cladding corrosion is discussed in connection with the possible causes of higher temperatures. Most other mechanisms for accelerated corrosion of fuel cladding resemble those for canister materials.

Indirect releases--Erosion corrosion, galvanic corrosion, and selective leaching are not likely to be important in a repository (Dayal et al., 1982).

Because the repository horizon is quite dry, most scenarios for the wetting of canisters, short of flooding of the repository, would probably lead to wetting only a portion of the canister. Under such circumstances, pitting corrosion could well occur if the metal is susceptible to it. Even if the bulk of the metal is immune, weld areas might be susceptible (NRC, 1985).

Stress-corrosion cracking will occur if there is stress, a susceptible metal, and an appropriate water composition. Canisters might (although a considerable rock movement would be required) be stressed by the surrounding rock mass (see Section 2.3.1), but even if they are not, residual stresses from fabrication and welding might be sufficient. Susceptibility might not be detected in the short-term (compared with repository lifetimes) tests conducted for canister design. Susceptibility might also be increased by sensitization. High-ionic-strength waters are most favorable to stress-corrosion cracking; salts could accumulate near waste canisters by the evaporation-based buildup mechanism described above; and in any case NRC (1985) cites a study showing stress-corrosion cracking of the proposed canister material in deionized water under gamma irradiation.

Susceptibility of canister materials to sensitization by long-term storage at elevated temperatures might not be discovered in the testing program. Sensitized metals could be subject to stress-corrosion cracking and intergranular corrosion (McCright et al., 1983).

Because the repository is in the unsaturated zone, relatively little hydrogen will be formed by radiolysis. What little hydrogen there is will be able to diffuse away without reaching high concentrations. Consequently, hydrogen attack on canisters is unlikely.

The main types of corrosion that could breach Zircaloy fuel cladding are uniform corrosion, stress-corrosion cracking, and hydriding (Gause and Soo, 1985). Stress-corrosion cracking would proceed outward from fission products contacting the inner surface of the fuel rod. (Aqueous stress-corrosion cracking of Zircaloy from the outside of the rods requires chloride ions and seems to be of importance only for salt repositories.) Both stress-corrosion cracking and uniform corrosion rates are very sensitive to temperature. The limiting factor in determining the allowable thermal power in a spent fuel package is the need to minimize cladding rupture by holding fuel temperature below 350° C (Gregg and O'Neal, 1985).

Less than 1 percent of the fuel rods in a repository will be clad in stainless steel. This material will corrode in a manner similar to stainless steel canisters, with details dependent on the particular steels involved.

Corrosion products may form colloids (Avogadro and de Marsily, 1984). These colloids might sorb radioelements and transport otherwise highly retarded species at higher speeds.

Sequences to be considered--The following sequences require further consideration:

64. Water drips or wicks onto canisters at specific locations, leading to buildup of brine deposits on small areas. These areas are focuses of localized attack.

65. Water drips or wicks onto canisters at specific locations, leading to buildup of brine deposits on small areas. The metal in these areas has been stressed by heat or welding, and stress corrosion cracking ensues.

66. The canister material is subject to stress-corrosion cracking, but the initiation time is too long to be detected in tests. A welded or heat-affected zone has been stressed. Canisters fail by this mechanism a few decades after the repository has been sealed.

67. Canisters are sensitized by long-term storage at moderately hot temperatures in the repository. Stress-corrosion cracking (or perhaps intergranular corrosion) ensues in a stressed welded or heat-affected zone.

68. Zircaloy cladding is subject to stress-corrosion cracking at repository temperatures, but initiation times are too long for detection in in-reactor service or in the repository testing program.

69. After canister breach, colloids of corrosion products sorb normally highly retarded radionuclides and carry them away unretarded by chemical reactions with the rock.

2.3.8 Chemical Reaction of Waste Package With Rock

Likelihood of occurrence--When water is in continuous contact with both waste packages and rock, chemical reactions are not only possible, but likely.

This section discusses only chemical reactions involving both rock and waste. Reactions undergone by the rock alone because of the imposed thermal and mechanical stresses and reactions between rock and repository construction materials are discussed in Section 2.3.10.

Indirect releases--Dissolved rock minerals in water that is in contact with spent fuel could react with uranium to form new solid phases. Uranium would dissolve, liberate the other radionuclides contained within the matrix, and precipitate in the new phase. The result would be dissolution of more spent fuel than would be predicted from the solubility of uranium in the natural waters. If water drips or flows from rock onto spent fuel, the amount of fuel dissolved would be limited by the concentration in the water of the material that precipitates the uranium. If rock movement or emplacement-hole failure has juxtaposed rock and waste so that water can simultaneously be in contact with both, then the material precipitating the uranium could be dissolved continuously from the rock, and the rate of waste dissolution would be limited only by the kinetics of the various dissolution and precipitation reactions.

A similar phenomenon is not to be expected with the canister, because the dissolution of canisters is controlled by kinetics and not equilibrium solubility. However, dissolved silicon, which may be present in high concentrations in waters in vitric tuff because the vitric tuff is in a metastable phase, promotes corrosion of Zircaloy fuel cladding (Gause and Soo, 1985).

Radioactive colloids might form either by coprecipitation of elements from both rock and waste or by adsorption of radioelements to colloids formed by alteration of the rock under the thermal, mechanical, and chemical stresses imposed by waste emplacement (Avogadro and de Marsily, 1984). Colloids might also be formed of waste elements themselves, when contaminated waters move into areas of lower temperature and therefore lesser solubility.

The size of americium colloids was measured to be large enough for most of them to be filtered out by the tuff under conditions of unsaturated matrix flow in the Topopah Spring unit (EA, Section 6.3.1.2.3). However, this filtration might not operate if fractures are saturated (NRC, 1985, p. 73). Also, colloids formed from natural materials or other waste constituents might have a different size distribution.

Sequences to be considered--The following sequences require further consideration:

70. Water dripping or running over waste contains ions that precipitate uranium. The precipitation reaction removes uranium from solution and increases the rate of fuel dissolution above what would be predicted from the equilibrium solubility of uranium.

71. Waste and rock are placed in close juxtaposition by mechanical failure of emplacement holes or drifts, or by small movements on faults. Water stands or runs in continuous contact with both. Reactions between uranium and rock minerals precipitate uranium, leading to relatively rapid dissolution of the spent fuel because the reaction is no longer constrained by the equilibrium solubility of uranium.

72. The high dissolved-silica content of natural waters entering the repository causes rapid corrosion of Zircaloy fuel cladding.

73. Colloids are formed from the rock by alteration under thermal, mechanical, and chemical stresses imposed by the repository. Normally well-retarded radioelements such as plutonium and americium sorb to the colloids and are transported with little or no retardation.

74. Waste-contaminated water reacts with rock, and colloid phases of minerals containing radioelements are formed by coprecipitation. These colloids are transported with little or no retardation.

2.3.9 Gas Generation

Gas generation is not a concern at an unsaturated repository because the waste is expected to be in contact with air. The pressure of any gas that is generated can easily be relieved within a relatively short distance by mass flow of the air through the fractures in the rock surrounding the waste.

2.3.10 Geochemical Alteration

This section discusses chemical reactions that are stimulated by the repository's heat and mechanical effects but involve only natural materials as reactants. Reactions in which both rocks and waste are reactants are treated in Section 2.3.8.

Likelihood of occurrence--Some geochemical alteration is likely under the influence of the thermal and mechanical stresses imposed on rocks around a repository. Most likely are (1) zeolite alteration reactions and (2) precipitation and redissolution of salts from water that evaporates near the repository during the thermal period.

Indirect releases--Hydrated zeolite minerals around a repository would release water if heated sufficiently. If enough water were freed by this mechanism, canister corrosion could be accelerated, and flow through fractures could occur. This does not lead to release, because during the period when rocks near the repository are being heated, the canisters are at a temperature above 100° C. The water is vaporized, and liquid water does not contact them. When the rocks near the repository cool, no water of hydration is being released.

Heat can also cause dehydration and alteration of minerals to less sorptive phases (Smyth, 1982; NRC, 1985, pp. 73-75). Even though only small amounts of sorptive clays and zeolites might be present, their relatively high sorptivity and concentration along fractures could make them major influences on geochemical retardation. Their alteration could significantly increase the rate of migration of dissolved radioactivity.

Clay or zeolite minerals produced by thermal alteration might clog pores. When the repository cooled and normal moisture fluxes resumed, flow could be diverted into fractures. However, experiments by Byerlee et al. (1983) suggest that tuff, unlike granite, does not have its permeability reduced by precipitation of minerals from water flowing into a cooler region, because of the large initial pore and vug spaces. Byerlee et al. do suggest that cement grouts or backfills might provide a source for greater quantities of fracture-filling precipitates.

The experiments of Byerlee et al. were conducted under saturated conditions, and therefore cannot be used directly for quantitative estimates of pore plugging. Braithwaite and Nimick (1984) calculate pore plugging under unsaturated conditions at Yucca Mountain. They assume that each unit of infiltrating water can only dissolve silica once, and they ignore the two-phase recirculation mechanism discussed in Section 2.3.4. Further calculations are necessary before this sequence can be eliminated from consideration.

As long as the repository remains sufficiently dry, water will not enter fractures, and downward-moving water will remain in the rock matrix. The water will dissolve minerals where it condenses and deposit them where it evaporates. The result could be a transfer of soluble minerals to the areas of evaporation, possibly resulting in the plugging of pores. When the temperature transient dies off and gravity-driven flow again becomes dominant, the rock matrix just above and below the repository might have much lower effective hydraulic conductivity, and flow might be diverted into fractures, significantly reducing flow times.

When flow resumes near the repository, precipitated salts would presumably redissolve. Concentrated, corrosive brines could be produced (NRC, 1985, p. 8). The redissolution might lead to an increase in matrix permeability sufficient to end fracture flow. Alternatively, water might not be able to reach many of the plugged pores, so that the salinity of the water would decline more rapidly and fracture flow would continue.

Precipitates might also plug fractures. If conditions are such that fracture flow occurs under natural conditions, flow after the thermal pulse ends could still be forced into larger-aperture fractures. The percolation velocity would thus be increased.

Another possible sequence of events is the depletion of waters passing through a hot repository in calcite, due to the declining solubility of calcite with rising temperature. When these waters reach the cooler rocks below the repository, they could dissolve out any calcite veins they might contain. (Calcite veins exist in the Paintbrush nonwelded unit, and might be found in the Calico Hills nonwelded unit as well.) The resulting open fissures, perhaps cleansed of insoluble residue by a piping effect, might be a pathway for fracture flow through the Calico Hills.

Hunter et al. (1983) discuss at length the possible loss of mechanical strength by rocks around a repository as a result of dehydration and rehydration as temperatures change. The Topopah Spring unit around the repository has a low content of zeolites that would be subject to these reactions; its mechanical strength comes from unaltered volcanic rock. Consequently, as Hunter et al. recognize, this phenomenon is not relevant to a repository located in the Topopah Spring.

Sequences to be considered--The following sequences require further consideration:

75. During the period of heating of rocks around the repository, minerals adjacent to the residual water-bearing pores are altered to clays. When the repository cools and a normal moisture flux resumes, these clays clog the pores, and water flows through fractures.

76. During the period of heating of rocks around the repository, zeolite minerals in fracture fillings are altered to less sorptive phases. This reduces geochemical retardation in the Topopah Spring welded unit.

77. Waters moving away from the hot region around the repository precipitate minerals derived from dissolved constituents of tuff and cements used in repository construction. These minerals clog pores, and divert subsequent flows through fractures.

78. Evaporation of ground-water in the hot zone near the repository horizon leaves precipitates that plug pores. As a result, when gravity-driven flow resumes, water near the repository is diverted into fractures. Initially, there is a pulse of corrosive brine due to redissolution of precipitates; but not all precipitates redissolve. The pores remain clogged, and fracture flow continues.

79. Evaporation of ground-water in the hot zone near the repository horizon leaves precipitates. When gravity-driven flow resumes, the precipitates redissolve, and after a short period of fracture flow the flow returns to the matrix. There is a considerable period of flow of corrosive brines with elevated dissolved solids.

80. There is fracture flow in the Topopah Spring welded unit even under undisturbed conditions. Chemical reactions induced by repository heat plug smaller-aperture fractures. After the thermal pulse ends, percolation is diverted into larger fractures, increasing its velocity.

81. Water passing through the warm region around the repository is depleted of calcite by temperature-induced precipitation. Below the repository, the calcite-poor water dissolves out calcite veins in the Calico Hills nonwelded unit and creates pathways for rapid movement through it.

2.3.11 Radiological Changes in Material Properties

Radiation is known to change mechanical and chemical kinetic properties of solid materials. The general effect is to increase the rates of chemical reactions and reduce plasticity and mechanical strength. The consequence could be an acceleration of any of the mechanisms of waste- and repository-induced release. Therefore, radiological changes in material properties are not discussed as initiating a separate class of release sequences, but must be taken into account in assessing the likelihood of the other sequences.

2.3.12 Radiolysis

Radiolysis will produce some oxidants and nitric acid in water near the waste canisters. Because the repository will not be saturated, the radiolytically produced gases will not cause any increase in pressure and will be able to freely diffuse away. Consequently, radiolytic gas generation will not create new pathways for waste release.

Radiolysis will alter the chemistry of waters near the waste. This needs to be taken into account in assessing rates of canister corrosion and waste dissolution in various sequences, but does not in itself constitute a different sequence.

2.3.13 Decay-Product Gas Generation

Decay-product gases will accumulate inside canisters until the canisters are breached. The pressure of these gases may put additional mechanical stress on the canisters, but they will presumably be designed to withstand this stress under expected conditions. In assessing scenarios in which external stresses are imposed on canisters, the internal gas pressure (due to both heating and decay-product gases) must be considered in calculating failure loads, but it does not constitute an independent failure mode.

Once they have escaped from waste canisters, decay-product gases will have effects similar to radiolytically produced gases. For reasons discussed in Chapter 1, their escape directly to the surface is not credible. They must be taken into account in assessing other scenarios but do not in themselves create a new mechanism for release.

2.3.14 Nuclear Criticality

Likelihood of occurrence--Criticality can occur in a spent-fuel canister only if the canister is loaded with fuel with greater than expected (more than about 1.5 percent by weight) content of uranium-235. Even then, criticality requires flooding of the canister with water, disintegration of the frame or fuel rods, and collapse of the spent fuel into a dense pile (O'Neal et al., 1984).

Otherwise, criticality can occur only if fissile nuclides are transported out of the canisters and concentrated at some other place. The most plausible way for this to happen is for plutonium (or perhaps americium) to dissolve in the oxidizing atmosphere of the repository and precipitate where the redox conditions of the ground-water change. Accumulation of plutonium at a highly sorptive zeolite seam is also conceivable. Over time, a critical mass of plutonium, which is much less than a critical mass of uranium because the fissile isotopes are a much higher proportion of the plutonium, might accumulate, in a manner similar to the formation of uranium deposits in sandstones.

This sequence presupposes breaching of canisters and dissolution of substantial amounts of plutonium, which is unlikely in itself. The chemical mechanisms for concentrating the plutonium are also unlikely. The redox mechanism requires that the plutonium-bearing waters not be excessively diluted in the tuff aquifer and that a small, well-delineated, reducing zone exist, the genesis of which is difficult to see in old volcanic rocks like those that make up Yucca Mountain. The sorption mechanism requires a zeolite with high exchange capacity that preferentially sorbs plutonium from water with many other constituents, many of them neutron poisons.

Direct releases--Because of the gradual accumulation of fissile nuclides and the presence of neutron-emitting isotopes of the same elements, an explosive criticality that would lead to direct releases is not credible.

Indirect releases--Criticality within a waste canister requires flooding with water, and therefore is only possible at temperatures below 95° C. Heating to this temperature would boil off the water that moderates the reaction and cause it to cease. Consequently, the maximum effect is heating to 95° C, which the repository is designed to accommodate.

Accumulation of plutonium on a sorbing zeolite seam could occur in the unsaturated zone. Either fast or slow criticality might be possible. The zone of criticality would constitute a heat source and thus prevent ingress of additional plutonium-bearing water during the period of criticality. Consequently, the heating would be self-limiting. Because of the lack of liquid water moving out of a heated zone in the unsaturated zone (Section 2.3.4 above), this would alter the inventory of radionuclides somewhat but would not lead to a new mechanism of release.

Below the water table, the presence of water makes only slow criticality plausible. The heat might well create a convective circulation cell. The convective cell might bring radioactivity down to the underlying carbonate aquifer, through which it could flow more rapidly to discharge points. However, we have shown so many necessary antecedents to be unlikely that the scenario may be disregarded as not being credible.

2.3.15 Microbial Activity

Likelihood of occurrence--West and McKinley (1984) and West et al. (1985) have shown that it is reasonable to expect some microbial growth in a deep-mined repository. The amount of such growth and the identity of the species to be expected are not well defined.

Microbes in a repository can be either naturally present in the host rock formation or introduced by repository construction or operation. The sources are difficult to distinguish (West et al., 1985), so all microbial effects will be discussed here.

Indirect releases--Mechanisms by which microbial activity could affect repository performance are listed by West and McKinley (1984) and West et al. (1985). Of the mechanisms listed by these authors, microbial deterioration of concrete, bentonite, and other materials used in the repository is of no concern here because an unsaturated-zone repository will not rely on the integrity of backfills or penetration seals for long-term safety.

Bacteria could accelerate corrosion of canisters or cladding by physically disrupting protective oxide coatings or by directly catalyzing corrosion reactions.

Sorption of nuclides onto microorganisms, or uptake and incorporation into the microorganisms, might accelerate waste dissolution. It could also make chemical sorption and matrix diffusion ineffective in retarding nuclide transport. West and McKinley also suggest that radionuclides could be transported by motile microorganisms, but this seems very unlikely in the dry conditions of Yucca Mountain.

West et al. suggest that microbes might alter ground-water chemistry. Such alterations are no doubt possible. However, they are unlikely to bring the water outside the range of situations already anticipated in the hydrothermal conditions of the period after repository closure. Therefore, no additional sequences should arise from this source.

<u>Sequences to be considered</u>--The following sequences require further consideration:

82. Microbial activity accelerates canister corrosion.

83. Microbial activity accelerates cladding corrosion.

84. Radionuclides are incorporated into microorganisms or sorbed on their surfaces. As a result, waste dissolution is accelerated. The nuclides taken up by microorganisms move at the velocity of ground-water, unaffected by chemical sorption or matrix diffusion.

3 SEQUENCES AND SCENARIOS

A repository at Yucca Mountain would have multiple barriers to release of radioactivity--the waste canister, fuel cladding, the resistance to dissolution of the spent fuel itself, and movement of released contaminants in three different hydrogeologic units: the unsaturated Topopah Spring welded unit, the unsaturated Calico Hills nonwelded unit, and the saturated tuff aquifer. Most of the disruptive sequences would affect only one or a few of the barriers. (Direct-release scenarios such as volcanic eruption and drilling are exceptions.) Before significant amounts of radioactivity can be released, all, or nearly all, of the barriers must be overcome.

In Chapter 2, 84 different sequences of disruptive events and processes with the potential of leading to releases of radioactivity were identified. Each of these sequences involves events and processes proceeding from a single cause. As it is possible that more than one of these causes might operate simultaneously, a very large number of scenarios could be constructed by combining the 84 sequences.

As is usual in studies of this type, sequences proceeding from several different causes often lead to very similar results. For example, many sequences lead to a localized zone of higher flux through the Topopah Spring welded unit. The consequences of such sequences are similar, and so they are typically addressed together in performance assessments.

In this chapter, the performance of each barrier under undisturbed conditions is described, and the failure sequences that affect the performance of that barrier are identified by number and classified. For convenience in reading these discussions, Appendix A lists all the sequences in numerical order.

The importance of the failure sequences rests not on their consequences considered in isolation, but on whether several failure modes operating at the same time can together overcome all the barriers so as to produce large releases. Therefore, Chapter 4 addresses each type of barrier failure and determines what additional failures are needed to cause release. It then identifies the scenarios, most of which are combinations of several failure sequences, that have the potential for leading to release of more than 100 curies of radioactivity. It is these scenarios that, it is suggested, require further analysis in the performance-assessment program.

3.1 Saturated Zone

In the preliminary performance assessments described in the Environmental Assessment (Sections 6.3.1.1.5 and 6.4.2.2.2.), the saturated zone was found to have relatively rapid ground-water flow and to make a negligible contribution to performance. Flow times along a 10-kilometer path in the saturated zone, calculated with an effective fracture porosity of 0.002, range from 200 to 2000 years (Sinnock et al., 1984). However, this conclusion rests on (a) use of a baseline scenario in which all flow in the unsaturated zone is through the rock matrix and (b) pessimistic assumptions about the hydraulic properties of the saturated zone. The argument that ground-water is moving much more slowly than assumed by the EA is supported by Claassen's (1983) interpretation of the geochemical data, suggesting that water has moved little since recharge events 10,000 years ago.

Furthermore, the matrix porosity of the saturated units is much larger than their fracture porosity, and so matrix diffusion (sometimes referred to as "physical retardation") can be expected to introduce an additional delay not included in the ground-water travel times. The delay factor of 100 suggested by Sinnock et al. is a reasonable upper bound on the effect of matrix diffusion, as the delay factor cannot exceed the ratio of total to fracture porosity. A delay approaching this magnitude would cause travel times to exceed 10,000 years, even with the most pessimistic estimates of water velocities.

Also, sorption will significantly delay most species in this zone.

These considerations suggest that after site characterization, the saturated zone could be found to act as a significant barrier to radionuclide migration. Delay times might be sufficient to yield acceptable performance in the event of rapid fracture flow through the unsaturated zone. Scenarios involving degraded performance of the saturated-zone flow system ought therefore to be considered here.

Some sequences (4, 16, and 50, which flood the repository, and 33 and 36, which do not) lead to creation of new ground-water discharge points closer to the repository. Such an event might reduce the distance to the accessible environment by a factor of 2, 3, or more and would correspondingly reduce the travel time through the saturated zone.

A variety of sequences (3, 7, 17, 22, 34, 35, 37, 51, and 62, which do not cause the water table to rise significantly, 2, 15, and 49, which do cause the water table to rise, and the flooding sequences mentioned in the previous paragraph) lead to faster flow in the saturated system, usually because of increased hydraulic gradients. Properties of the saturated flow system that might cause it to have slow flow have not yet been defined, and so specific analyses of these sequences are not possible at this time.

A third group of sequences (69, 73, 74, and 84) involve formation of radioactive colloids (or microbes). Colloidal particles might be retarded by geochemical interactions with rocks much less than dissolved radioactive species are. In this way, formation of colloids could increase migration velocities in all three zones for ground-water movement. If the time required for moisture to move through the unsaturated zone is reduced below 10,000 years by some other cause, formation of colloids might lead to release of elements present in large quantities (such as plutonium and americium) whose release would otherwise be prevented by chemical retardation and matrix diffusion.

3.2 Calico Hills Nonwelded Tuff Unit

Montazer and Wilson (1984) identify two principal hydrogeologic units in the volume between the proposed repository level and the water table: the Topopah Spring welded unit and the Calico Hills nonwelded unit. The properties of these units differ sufficiently that different causes are often needed to reduce their effectiveness as barriers, and so they are treated separately here.

The lower of the two unsaturated-zone units, the Calico Hills nonwelded unit, is composed of two subunits referred to as the zeolitic and vitric facies. The vitric facies has a higher matrix permeability and is less fractured than the Topopah Spring unit. The zeolitic facies has a low matrix permeability, perhaps comparable to the Topopah Spring matrix permeability, and has a discontinuous fracture system (Montazer and Wilson, 1984). Consequently, fracture flow is less likely to occur in the Calico Hills than in the Topopah Spring unit under both present and possible future conditions, assuming both units remain unsaturated.

The geometric mean of measured matrix hydraulic conductivities in the zeolitic facies of the Calico Hills is about 3 millimeters per year, with effective porosity at least 1.6 percent and probably about 23 percent and saturation about 90 percent (Montazer and Wilson, 1984). This implies that flow in the unit is confined to the matrix. Travel times for a thickness of 50 meters may be computed to range from an expected 10,000 years for flux of 0.1 millimeter per year and effective porosity of 23 percent to a very conservative 200 years for flux of 3 millimeters per year and effective porosity of 1.6 percent.

The zeolites of this unit have strongly sorptive properties.

Local alteration of the properties of the Calico Hills unit or of the hydraulic system around it, as in sequences 6, 20, 21, 23, 53, and 81, might lead to fracture flow in localized areas.

The unit would be eliminated as an unsaturated-zone barrier altogether if the water table were to rise above it. This elimination occurs in sequences 2, 15, and 49, in which the water table does not rise so high as the repository, and in sequences 4, 16, and 50, which involve flooding of the repository itself.

3.3 Topopah Spring Welded Tuff Unit

The minimum thickness of the Topopah Spring welded unit below the repository is just under 50 meters. If there is no fracture flow, the unit's moisture content of 10 percent and steady-state flux of 0.5 millimeter per year give a water travel time of 10,000 years. Because the unit has high matrix saturation, water content will vary little with flux, and travel time will be roughly inversely proportional to flux. With a less conservative flux of 0.1 millimeter per year, travel time would be 50,000 years.

It is possible that fracture flow is occurring in the Topopah Spring under present conditions. Fracture flow would be rapid; Sinnock et al. (1984) estimate that for a flux of 4 millimeters per year through well-connected fractures, the time to travel 50 meters would be 10 years. Thus, the travel time for a flux of 0.1 millimeter per year through well-connected fractures in the Topopah Spring unit (in addition to whatever flux is passing through the matrix) would be between 10 and 400 years. These estimates are consistent with Thordarson's (1965) measurement of 0.8 to 6 years as the age of water perched in fractures in tuffaceous beds at the somewhat wetter site of Rainier Mesa.

Even if water flows in fractures, dissolved radionuclides could move more slowly than the water in the fractures because of matrix diffusion. Experimental evidence is lacking on the effectiveness of matrix diffusion in an unsaturated medium. Sinnock et al. estimate that if matrix diffusion operates, unsorbed contaminants should move more slowly than the water velocity in the fracture by a factor of 100 to 400. If this is the case, contaminant travel times will exceed 10,000 years if the fracture-flow travel time is more than 25 to 100 years.

The most numerous failure sequences are those that affect the Topopah Spring welded tuff unit. Principal among these are sequences leading to faster movement of ground water through the unit. The increased water velocity could be due either to a generalized initiation of fracture flow throughout the unit (sequences 1, 2, 11, 31, 48, 49, 59, and 78, in which the fracture flow is caused by increased flux, and sequences 43, 47, 75, and 77, in which other physical mechanisms operate) or to creation of a localized zone of higher flux passing through an area where canisters are emplaced (sequences 5, 8, 9, 10, 12, 13, 14, 19, 25, 26, 32, 38, 39, 41, 42, 45, 46, 52, 57 and 61). It must be remembered that significant fracture flow may already be occurring in the unit, if the percolation rate is higher than the current best estimate or if the flux at the site is not as close to steady state as the conceptual model of Montazer and Wilson (1984) assumes. Sequences 18, 54, and 80 assume that such is the case and involve increases in the velocity of water movement in the fractures.

Geochemical retardation in the unit might be reduced, either by formation of colloids (sequences discussed above) or by thermal alteration of sorbing minerals (sequence 76). And, of course, if the repository were flooded by a rise in the water table, there would no longer be an unsaturated-zone barrier.

3.4 Canisters

As long as uniform corrosion is the mode of canister corrosion, the lifetime of the canisters is estimated at 3000 to 30,000 years (EA Section 6.4.2.2.1).

The simplest mechanism that would accelerate canister corrosion is an increase in the amount of water flowing past the canisters. This could follow from either a generalized increase in the amount of water percolating through the Topopah Spring unit (sequences 1, 2, 11, 31, 48, 49, 59, and 78) or formation of a localized wet region (any of the sequences of this type listed in the previous section). The sequences in which the repository is flooded are, of course, extreme examples of this phenomenon. It should be noted, however, that measurements of corrosion rates are based on extensive wetting of the metal (McCright et al., 1983). Therefore greater wetting of canisters than suggested by current hydrologic models would in itself probably not cause corrosion to proceed significantly faster than the tests indicate.

A variety of physical and chemical changes in the waste package or its environment could initiate faster localized corrosion mechanisms. Sequences 27, 29, 55, 58, 60, 64, 65, 66, 67, 79, and 82 are of this type.

Sequences 12, 30, 56, and 63 involve mechanical breakage of canisters.

3.5 Fuel Cladding

More than 99 percent of fuel rods are clad in Zircaloy; the remainder are clad in stainless steel. Most cladding will be intact at waste emplacement; for boiling water reactors, only between 0.01 percent and 1 percent will have failed (EA, Section 6.4.2.2.2). Evidence to date indicates that the time to penetration of the remaining rods will be at least 300 years, and possibly much longer (Gause and Soo, 1985). Some radioactivity is present on the outside of the rods, due in part to activation of crud; cladding will not be a barrier to the release of this contamination.

In general, sequences involving increased water flux through the repository will accelerate corrosion of cladding as well as canisters. Such sequences are those involving increased percolation through the Topopah Spring unit (described in the preceding section) and sequences 27, 58, and 60, which put increased moisture in contact with the waste package without increasing the flux through the geologic unit. Because corrosion from inside the fuel rods rather than from the outside environment may be the limiting factor in cladding performance, it is not certain whether this would shorten cladding life. Furthermore, the limited data on cladding corrosion are mostly based on complete wetting.

Sequences 68, 72, and 83 involve mechanisms that accelerate the rate of cladding corrosion. Elevated temperatures can also accelerate cladding failure (Gregg and O'Neal, 1983); sequences 27 and 28 are of this type.

Forces causing mechanical breakage of canisters (sequences listed in the previous section) would probably lead to breakage of cladding as well.

The EA (Section 6.4.2.2.2) explicitly neglects the effect of zirconium fuel cladding in preventing leaching of spent fuel. However, waste packages are being designed to minimize cladding rupture (Gregg and O'Neal, 1983), and cladding could well turn out to play a significant role in waste-package performance.

3.6 Waste Dissolution

Sinnock et al. (1984) calculate waste-dissolution rates from the equilibrium solubility of uranium. These dissolution rates depend linearly on the moisture flux through the unsaturated zone and the fraction of the water passing through the repository that comes into contact with waste. For a moisture flux of 0.1 millimeter per year and 0.25 percent of the water contacting waste (the expected value for vertically emplaced canisters; horizontal emplacement gives a figure one order of magnitude higher), the waste dissolves at a rate of about 1 part in 100 billion per year.

How do waste-dissolution rates affect releases to the accessible environment? Because sorption reactions will probably prevent release of most waste constituents to the accessible environment within 10,000 years even in scenarios in which ground water moves enormously faster than expected, the answer to this question depends on the least retarded species. Assuming 70,000 MTU of spent fuel in the repository, the total inventory of the unretarded nuclides carbon-14 and iodine-129 is about 33,000 curies at 5,000 years. If the waste dissolves at a rate of less than 1 part per 10 million per year, less than 100 curies of the unretarded species will dissolve within 10,000 years. The slightly retarded technetium-99 has an inventory of about 900,000 curies, so to prevent dissolution of 100 curies in 10,000 years requires an overall dissolution rate below 1 part in 100 million per year.

If percolation rate is the only parameter changed in these calculations, dissolution of 100 curies of technetium would require a flux of 100 millimeters per year for vertical emplacement and 10 millimeters per year for horizontal emplacement. Dissolution of 100 curies of iodine and carbon would require a flux of 1000 to 10,000 millimeters per year. Fluxes of 100 millimeters per year or more, averaged over the repository area of several square kilometers, are unreasonable even after the most extreme climate changes if the repository remains above the water table.

It should be emphasized that these calculations assume congruent release of all species from the waste. KBS (1983, p. 11:2) reports that for a "small fraction" of fuel rods, as much as 30 percent of the iodine can be leached within a few weeks. The total inventory of iodine is 2310 curies, so nearly 5 percent of it would have to leach quickly to exceed 100 curies. Indeed, even release of the entire iodine inventory would not violate the EPA standard. We may assume that KBS's "small fraction" is small enough that the phenomenon may be neglected; if releases as small as 100 curies are of concern, this assumption will have to be confirmed by experiment.

Any of the mechanisms discussed in Sections 3.3 and 3.4 that lead to contact of increased amounts of water with the waste package would tend to increase waste-dissolution rates. Because performance assessments such as Sinnock et al. (1984) assume that waste-dissolution rates are solubility-limited, increases in water flux would change the calculated waste-dissolution rates.

Chemical reaction mechanisms might also increase the rate of waste dissolution. Any of the colloid-formation mechanisms discussed in Section 3.1.1 could have this effect; sequences 70 and 71 involve additional means of accelerating dissolution.

3.7 Summary of Sequences Affecting Each Barrier

The above discussion allows us to list a relatively small number of types of barrier failure. The sequences may be classified as follows, with sequence 12 falling into two categories.

A. Direct release - 24, 40, 44.

B. Repository flooding - 4, 16, 50.

C. Colloid formation - 69, 73, 74, 84.

D. Increased water flux through the unsaturated zone - 1, 11, 31, 48, 59, 78.

E. Localized regions of high flux through the repository - 5, 8, 9, 10, 12, 13, 14, 19, 25, 26, 32, 38, 39, 41, 42, 45, 46, 52, 57, 61.

F. Water diverted toward the waste package - 27, 58, 60.

G. Accelerated dissolution mechanisms - 70, 71.

H. Accelerated cladding-corrosion mechanisms - 28, 68, 72, 83.

I. Accelerated canister-corrosion mechanisms - 29, 55, 64, 65, 66, 67, 79, 82.

J. Canister breakage - 12, 30, 56, 63.

K. Fracture flow in the Topopah Spring welded unit without increased moisture flux - 43, 47, 75, 77.

L. Reduced sorption in the Topopah Spring welded unit - 76.

M. Water-table rise above the Calico Hills nonwelded unit - 2, 15, 49.

N. Fracture flow in the Calico Hills nonwelded unit - 6, 20, 21, 23, 53, 81.

O. New discharge points - 33, 36.

P. Faster flow in the saturated zone - 3, 7, 17, 22, 34, 35, 37, 51, 62.

Q. Acceleration of pre-existing fracture flow - 18, 54, 80.

The barriers affected by these types of failures may be summarized as follows:

Waste form - A, B, C, D, E, F, G, M.

Cladding - A, B, D, E, F, H, J, M.

Canister - A, B, D, E, F, I, J, M.

Topopah Spring welded tuff unit - A, B, C, D, E, K, L, M, Q.

Calico Hills nonwelded tuff unit - A, B, C, D, E, M, N.

Saturated tuffs - A, B, C, M, O, P.

4 POTENTIAL RELEASE SCENARIOS

Most of the disruption sequences identified in Chapter 2 and listed for convenience in Appendix A do not, in themselves, have the potential to cause release of 100 curies or more within 10,000 years; additional disruptions affecting other barriers would be needed. The scenarios analyzed in performance assessments will therefore usually involve multiple disruptions. The purpose of this chapter is to provide a means of identifying the combinations of disruptive sequences that form potential release scenarios and to describe appropriate ways of analyzing them further.

Each of the 17 classes of failure sequences identified in Chapter 3 is discussed here. First, the barriers that would be affected are identified. Second, methods for analyzing the sequence as part of a failure scenario are recommended. In some cases, further work on the sequences's likelihood of occurrence is recommended, in the belief it may be shown not to be credible. For most sequences (other than those that are likely to be shown not to be credible), methods of consequence analysis are briefly outlined. No attempt is made to provide a detailed exposition of performance-assessment methods.

The point of this analysis is to identify scenarios that would lead to releases of radioactivity, not to assess compliance with Nuclear Regulatory Commission standards governing individual barriers. There are scenarios one could imagine in which the ground-water travel time would fall below 1000 years, canisters would last less than 300 years, or waste dissolution would proceed faster than 1 part per million per year, without causing a significant release of radioactivity to the accessible environment. (For example, if canisters are intact for 10,000 years, ground-water hydraulics will not affect the amount released.) Such scenarios are not identified as release scenarios here. The NRC performance standards govern ground-water travel times only before repository construction, and waste-package performance only in the case of "anticipated processes and events" (NRC, 1983, 60.113). It is the EPA standard (EPA, 1985) governing releases of radioactivity that must be satisfied both in expected circumstances and after unanticipated disruptive events or processes.

4.1 Direct Release

Sequence numbers--24, 40, 44.

Barriers affected--These sequences bypass all barriers; no additional disruptions or failures are needed to cause release.

Methods of analysis--volcanoes--Volcanic eruption (sequence 24) is the disruptive scenario at Yucca Mountain that has been most intensively analyzed to date. Methods for analyzing its probability (Crowe et al., 1982) and consequences (Logen et al., 1982) are already well established.

The final EPA regulations set the cutoff probability below which scenarios may be ignored at 0.0001 in 10,000 years. Published probability calculations are based on a range of assumptions about what geographic area and time period should be used to calculate a rate of eruption. Only the more pessimistic assumptions yield probabilities of disruption above 0.0001. Further analysis of the geologic controls on Great Basin volcanism might show that these assumptions are inappropriate.

The amount of radioactivity released in a volcanic eruption is calculated by assuming that all waste in a volume equal to the volume of feeder dikes seen at old volcanoes is erupted (Logan et al., 1982). As Logan et al. point out, volcanic rocks typically incorporate much less country rock than would be predicted from this assumption. Further study of the geology of volcanoes might show that a much smaller volume of waste would be incorporated in magma, allowing a concomitant reduction in the calculated release of radioactivity.

Methods of analysis--inadvertent removal by miners or drillers--Scenarios in which waste is brought to the surface as drilling or mining waste (sequences 40 and 44) rest on a series of questionable hypotheses about further actions by societies and individuals (Koplik et al., 1982).

The most recent calculation of their probability, a treatment of drilling by Smith et al. (1982), is no more satisfying than any of the earlier computations criticized by Koplik et al. Smith et al. hypothesize that knowledge of a repository's existence and of the lack of mineral resources at the disposal site would be reforgotten every 50 years. At a salt site, this would lead to immediate drilling, giving an intrusion frequency of 0.02 per year. The assumption made here, that drilling rates in salt will continue indefinitely at the high levels associated with an oil-based economy, seems unlikely. However, Smith et al. proceed to assert that drilling frequencies would be the same in shale as in salt and less by a factor of at least 2 in basalt and 10 in granite because basalt and granite are less likely to contain useful resources. The salt drilling frequency of 0.02 per year is divided by these factors to obtain the drilling rate in the other media. Because the salt frequency is based on the rate of forgetting rather than on the attraction of the salt as an exploration target, the logic used to calculate drilling rates in other media seems dubious.

In our opinion, it is not reasonable to try to calculate numerical probabilities for scenarios involving accidental human intrusions of this sort. A more appropriate way to handle them is to prepare a narrative laying out the events that must occur before waste is released in an uncontrolled manner, giving reasons for thinking each of them likely or unlikely. DOE, NRC, and the interested public can then form their own opinions as to whether the scenarios should be a matter of concern. This sort of nonnumerical judgment is made regularly by courts that decide whether something has been proven "beyond a reasonable doubt." If the EPA (1985) regulation is to be interpreted as requiring a numerical calculation of the probability of these scenarios, it will be difficult to determine whether any site meets it.

4.2 Respository Flooding

Sequence numbers--4, 16, 50.

Barriers affected--Flooding of the repository would lead to accelerated waste dissolution and would eliminate the unsaturated zone as a barrier. In sequences 4 and 50, it would be associated with a wetter climate and so with faster water movement in the saturated zone. If the water table rose much above the repository, new discharge points and shorter paths for contaminant migration might develop.

Flooding would probably also accelerate corrosion of canisters and fuel cladding. Because corrosion tests involve extensive wetting of the metals, flooding might not cause faster corrosion than assumed in performance assessments.

Methods of analysis--As stated in Section 2.1.1, there is an excellent chance that further study will show that repository flooding scenarios are not credible. Analysis should therefore be directed to the likelihood and not the consequences of these scenarios.

Natural rises in the water table (sequence 4) are not expected to exceed those that occurred during the Quaternary. As discussed in Section 2.1.1., a variety of evidence shows that Quaternary water tables remained well below the repository level. The one possibly discordant piece of evidence is the spring and lakebed deposits in Crater Flat. Further geological study of these deposits should be pursued to determine their age and relationship to regional water tables. Other geologic evidence bearing on past water levels should also be analyzed. Current U.S. Geological Survey research on Quaternary climates in the Amargosa Desert area, although not funded by the repository program, will probably be useful for this purpose (I.J. Winograd, U.S. Geological Survey, oral communication, 1985).

For climate modification to cause a water-table rise exceeding that observed during the Quaternary (see Section 2.2.17), the climate over a considerable area would have to become wetter during the next 10,000 years than it was at the extreme pluvials. This seems extremely unlikely, but should be pursued with appropriate consultants.

The 500-foot-plus rise in the water table caused by faulting in sequence 16 seems inherently implausible. A better characterization of the ground-water barriers around Yucca Mountain would probably show it not to be credible.

4.3 Colloids

Sequence numbers--69, 73, 74, 84.

Barriers affected--Colloidal particles do not have the same retarding chemical reactions with rock as dissolved substances, and they diffuse into the rock matrix much more slowly than solutes, if at all. In the extreme case, radioactive colloids might travel with the same speed as ground water through both saturated and unsaturated zones.

Waste dissolution might be accelerated by the same process as forms the colloids (sequences 74 and 84). One would not expect a similar acceleration of corrosion, because corrosion rates are kinetically controlled rather than equilibrium-limited, and so removal of metal from solution by colloid formation would not drive the reaction faster.

Even in the worst case of colloid transport, water travel times and canister and cladding lifetimes would still serve to delay the initial release of radioactivity.

Methods of analysis--Study of filtration and chemical retardation of colloids in tuff, especially in unsaturated tuff, may make it possible to eliminate colloids as an important mechanism of faster transport of radioactivity. The literature on colloid migration, as applicable to radioactive-waste repositories, is summarized by Hunt et al. (1985). Some calculations relevant to Yucca Mountain are presented by Travis and Nuttall (1985).

Particularly useful would be studies of filtration in porous flow through the Calico Hills unit and fracture flow through the Topopah Spring unit. To prevent any release within 10,000 years, it would be sufficient for filtration to slow colloids by some small factor in the former unit or a large factor in the latter.

The chemistry and physics of colloid formation could also be studied to bound the quantity of radioactivity that might be carried. Similarly, chemical constraints on microbial life could be calculated to bound the possibility of radionuclide uptake by microbes (West et al., 1985).

4.4 Widespread Increase in Percolation

Sequence numbers--1, 11, 31, 48, 59, 78.

Barriers affected--Moisture flux through the repository may increase as a consequence of climate change, either natural or artificial (sequences 1 and 48), in response to very rare precipitation events (sequence 11), because of irrigation (sequence 31), or as a result of drainage of hot condensate collected above the repository (sequences 59 and 78).

As far as is now known, any increase in percolation might have a reasonable chance of leading to fracture flow in the Topopah Spring welded unit. However, fractures do not seem to provide a continuous flow path in the Calico Hills nonwelded unit (Montazer and Wilson, 1984). Therefore, to overcome the barrier represented by the Calico Hills unit, either the increase in percolation would have to be sufficient to saturate the Calico Hills, or an additional event would be needed to create pathways for fracture flow in the Calico Hills.

Increased percolation rates from whatever cause would tend to accelerate waste dissolution. In those sequences involving climate changes or precipitation events, canister and cladding corrosion may be accelerated (but perhaps not beyond the values assumed in performance assessments), and greater regional recharge would tend to increase ground-water velocities in the saturated zone. The sequences involving condensate are not associated with faster ground-water movement in the saturated zone, but condensate probably has a more corrosive chemistry than natural waters.

<u>Methods of analysis</u>--A three-step process may be used to evaluate these sequences. One must first assess the likely magnitude of increased percolation. Next, it must be determined whether percolation through the Calico Hills is sufficient to cause saturation or perching. Finally, if these considerations do not dispose of these scenarios, a full calculation of consequences will be required.

For scenarios involving condensate drainage, the magnitude of increased percolation may be estimated through numerical modeling studies estimating the amount of condensate collecting above a repository. It is not clear whether one-dimensional models will provide an acceptable upper bound on the phenomenon, or whether two- or three-dimensional models must be used. If the latter, availability of adequate models may be a problem.

For scenarios involving climate change, the best approach to estimating the magnitude of future percolation is probably an indirect one: to find the maximum reasonable rise of the water table from geologic evidence of past water tables and to back-calculate past recharge rates. The geologic studies of past climates mentioned in Section 4.2 must be used here.

A combination of these two approaches may be needed to address the rare precipitation event. The magnitude of precipitation (or at least of flooding) would be estimated from the geologic record, and the effects on the unsaturated zone would then be calculated with numerical models.

The irrigation sequence is perhaps the most difficult to address. One could at least bound the magnitude of the effect by assuming that future irrigation practices will use water no less efficiently than present practices, assuming a rate of infiltration corresponding to the worst current practice throughout the area it would be reasonable to irrigate, and using a cross-sectional numerical unsaturated-flow model to estimate the flux through the repository.

The next step is to determine whether future percolation rates will be sufficient to cause perching or saturation of the Calico Hills. For the climate-change and precipitation event sequences, saturation or perching can be seen directly from the past water levels. For the condensate-return sequences, a one-dimensional pencil-and-paper calculation should give an adequate answer. Two-dimensional numerical modeling will probably be needed for the irrigation sequence.

If the calculation shows that all effluent from the repository still reaches the water table by porous flow through the Calico Hills, the 5000-year-plus time delay for unretarded species implies that any element with a retardation factor of 2 or more will not be released within 10,000 years. Release of more than 100 curies from the repository is still possible, but it will be very difficult to violate the draft EPA standard. Because the EPA standard allows release of nearly all of the possibly unretarded elements carbon, technetium, and iodine, nearly complete leaching of the waste in the first 5000 years is required for it to be violated.

If consequence calculations are needed, existing models will probably be adequate. Models of corrosion and waste dissolution at Yucca Mountain generally include the percolation rate as a parameter (Sinnock et al., 1984), so no new data or models will be required for that part of the calculation. (Scenarios in which wastes are contacted by saline condensate are exceptions to this observation; experimental work on salinity effects on corrosion would be needed to address them fully.) In condensate scenarios, present-day saturated-zone flow velocities could be used; for climate-change scenarios, the effect of increased regional recharge on the flow system would have to be considered.

4.5 Localized Increase in Percolation

Sequence numbers--5, 8, 9, 10, 12, 13, 14, 19, 25, 26, 32, 38, 39, 41, 42, 45, 46, 52, 57, 61.

Barriers affected--In these sequences, only a small fraction of the waste packages is located in a zone of enhanced percolation. The enhanced percolation can lead to faster waste dissolution and, perhaps, corrosion for those packages. This could lead to release of more than 100 curies. However, it is impossible to exceed the release limits in the EPA (1985) standard, which allow release of nearly half of the carbon, iodine, and technetium in the waste, by failures that affect only a small fraction of the waste packages unless there is fracture flow or saturation in the Calico Hills unit.

Because these sequences do not involve overall increases in recharge, they will not cause the Calico Hills unit to saturate. While fracture flow through the Calico Hills unit is possible in the future, there is no evidence for significant fracture flow now. Consequently, for percolation to lead to significant releases, some future event must occur to induce local fracture flow through the Calico Hills.

Locally increased percolation would have no significant effect on travel times in the saturated zone.

Methods of analysis--Methods for calculation of the consequences of these scenarios are very similar to those for scenarios involving general increases in percolation. Moisture fluxes must be calculated from physical models for the initiating causes of the wet zones.

The only additional factor entering the calculation is the area of the wetter zone. The starting point for this calculation is a geometric calculation of, for example, the ratio of the cross-sectional area of rock fractured by a fault to the area of the repository. In those cases where the cause is an event occurring above the repository (sequences 8, 9, 10, 12, 14, 19, 32, 39, 41, 42, 45, 46, and 57), one must also calculate the lateral spreading of the moisture. This spreading may be due to suction forces, lateral dispersion, or both. Such spreading is an active area of research at the present time (e.g., Yeh et al., 1985a; 1985b; 1985c).

4.6 Wetting of Waste Package

Sequence numbers--27, 58, 60.

Barriers affected--These sequences involve accelerated corrosion of cladding and canisters and faster dissolution of waste packages. Because there is no change in the amount or spatial distribution of moisture moving through the system, flow times do not change.

Methods of analysis--It may well be possible to design and operate the repository in such a way that these sequences are not credible. Consequently, the first task in evaluating them is to enumerate any design features and operational procedures tending to prevent them. With this information, one may assess the credibility of the failure sequences.

If the sequences are credible, experimental work will be need to define their effect on canister corrosion. Sequence 58, in which water flows out of the rock matrix onto canisters, may turn out to correspond to the expected conditions of canister corrosion, in which case canister materials will presumably be tested under corresponding conditions. However, corrosion under the conditions of sequences 27 and 60, in which droplets of water fall on a hot canister, could probably be predicted only by testing it directly.

Waste-dissolution rates in these sequences can be predicted from the models used to predict waste dissolution under expected conditions. The proportion of total moisture flux that contacts the waste canisters is one of the parameters in the model of Sinnock et al. (1984). One need only increase the value of this parameter.

4.7 Accelerated Waste Dissolution

Sequence numbers--70, 71.

Barriers affected--These sequences affect only waste dissolution.

Methods of analysis--Both of these sequences rest on the hypothesis that there is a solid uranium-bearing phase of the waste-water or rock-waste-water assemblage that is thermodynamically more stable than the uranium oxide in the fuel. One might test that hypothesis with a geochemical equilibrium calculation (probably using a computer model) to determine what the stable phases are in the system. One could then study the kinetics of the reactions identified by the equilibrium studies to determine whether uranium dissolution would be accelerated.

Alternatively, these sequences could be tested by direct experiment with appropriate mixtures of spent fuel, water, and rock.

Analysis of these sequences, which affect only the dissolution barrier, may not be necessary. A combination of failures of other barriers sufficient to make dissolution rates matter may not be credible.

4.8 Accelerated Cladding Corrosion

Sequence numbers--28, 68, 72, 83.

Barriers affected--These sequences affect only the fuel cladding.

Methods of analysis--The likelihood and consequences of sequences 28 and 72, in which corrosion is accelerated by temperature or water composition, can be evaluated by laboratory tests. The time required to run these tests to reach a desired level of confidence might, however, be too long to be practical. Tests can also be used to evaluate sequence 83, in which corrosion is accelerated by microbial action; however, these tests are more difficult to plan because the microbial species involved must first be identified.

Sequence 68, involving stress-corrosion cracking, raises a difficult issue. Dayal et al. (1982) point out that in some cases tests lasting as long as several weeks have been totally inadequate to determine the resistance of metals to cracking. Additional research will be needed on this subject if repository safety must rely on the resistance of metals to stress-corrosion cracking.

4.9 Accelerated Canister Corrosion

Sequence numbers--29, 55, 64, 65, 66, 67, 79, 82.

Barriers affected--Most of these sequences affect only the canisters. Sequence 79, based on flow of corrosive, high-salinity condensates, also affects the flow in the unsaturated zone. The effect on the flow barriers of this sequence is similar to, but less long-lived than, that of sequence 78, which is discussed in Section 4.4.

Methods of analysis--The effects of these sequences on canister performance can only be assessed through laboratory testing. As mentioned in the previous section, such testing will be difficult for the sequences involving stress-corrosion cracking (55, 65, and 66), and the same may be true for the sequence involving sensitization (67).

Sequence 29, involving defective manufacturing, affects only a limited number of canisters. An estimate of the maximum number of canisters that would be affected could probably be obtained from historical records of failure of similar systems.

4.10 Canister Breakage

Sequence numbers--12, 30, 56, 63.

Barriers affected--The only barriers affected are the canisters and cladding. Sequence 12, in which the canisters are broken by fault movement, could also create a localized zone of greater moisture flux, affecting flow barriers and dissolution rates.

Methods of analysis--The consequence of canister breakage is immediate loss of the barrier; therefore, the only aspects of the sequences to be investigated are their likelihood and the number of canisters that would be affected.

For breakage by fault movement (sequence 12), likelihood can be assessed by studying past movement of faults through the repository, taking account of the detailed geometry of waste emplacement (faulted areas may be avoided). The number of broken canisters can be estimated from geometrical considerations if one assumes that the active fault is no wider than other faults in the vicinity.

Sequences 30 and 63, in which canisters are broken by accident or by rockbursts, can be evaluated from historical records of mine accidents and from operating experience during site characterization.

Sequence 56, involving breakage due to thermal expansion of surrounding rock, must be assessed by calculating the magnitude of rock movement. Depending on the magnitude of the effect and on details of package and hole design, detailed numerical calculations may not be necessary.

4.11 Fracture Flow Without Increased Flux

Sequence numbers--43, 47, 75, 77.

Barriers affected--Sequences 43 and 47, in which fracture flow is caused by drilling-induced changes in water chemistry, could affect both the Topopah Spring and Calico Hills units. Sequences 75 and 77, in which fracture flow is caused by pore clogging by minerals precipitated during the thermal period, would affect principally the Topopah Spring; any portions of the Calico Hills that are within the thermally perturbed zone might also be affected. Aside from a possible minor increase in the amount of water contacting the waste package because of flow diversion out of the clogged pores of the rock matrix into fractures, none of these sequences would significantly affect other barriers.

Methods of analysis--If fracture flow occurs, the fracture-flow velocity will have to be used in performance assessments. Matrix diffusion might then be important, as discussed above.

The sequences involving drying of pores by surfactants (43 and 47) have not previously been discussed in the literature. A little theoretical or practical study may suffice to show them not credible. Experiments on the behavior of unsaturated tuffs under heating may also make it possible to rule out the clogging scenarios.

4.12 Reduced Sorption in the Topopah Spring

Sequence number--76.

Barriers affected--The only barrier affected by this sequence is the Topopah Spring welded unit.

Methods of analysis--This sequence can be of importance only if there is fracture flow in the Topopah Spring unit. In the absence of fracture flow, moisture movement will be so slow that even unretarded species will not be able to pass through the unit in 10,000 years. Therefore, any analysis of the sequence should focus on sorption sites in the fractures and sites adjoining the fractures that are accessible by matrix diffusion.

One must first identify in the field the specific minerals providing sorption sites in the fractures and in pores near the fractures. Then the stability of these minerals must be tested experimentally, using fluids that reasonably represent the water-air-steam environment of a repository.

4.13 Water-Table Rise

Sequence numbers--2, 15, 49.

Barriers affected--If the water table under the repository rises above the Calico Hills unit, even if it does not rise far into the

Topopah Spring unit, the containment ability of the Calico Hills could be considerably decreased. The mechanism that causes the rise of the water table in sequence 15 also increases the hydraulic gradient in the saturated zone, reducing travel times there. It is also possible that with even a slight rise of the water table into the highly transmissive Topopah Spring, the increase in transmissivity would raise ground-water velocities without any change in gradient.

Water-table rise in itself does not significantly affect the flow time in the Topopah Spring welded unit. However, an increase in recharge causes the water-table rise in sequences 2 and 49. This would raise the moisture flux through the Topopah Spring and could well induce fracture flow in that unit. An increased moisture flux would also tend to accelerate canister corrosion, cladding corrosion, and waste dissolution.

<u>Methods of analysis</u>--The first priority in determining the likelihood of these sequences is to measure the saturated vertical hydraulic conductivity of the Calico Hills unit in situ. Geological studies of the unit would be extremely useful also if evidence of past water-table levels could be found. This evidence would help determine how large an increase in recharge would be needed to saturate the unit.

Sequence 15 is based on breach of the ground-water barrier north of repository by a fault; it does not depend on an increase of recharge. A better understanding of the nature of the barrier would be needed to assess its likelihood.

Methods for calculating the consequences of scenarios involving water-table rise are similar to methods for analyzing the expected case. Moisture fluxes and velocities in the Topopah Spring unit can be calculated by the same methods as in the increased infiltration scenarios discussed in Section 4.4. A three-dimensional or cross-sectional ground-water flow model of the system, with recharge or barrier transmissivity adjusted to reflect the failure sequence, must be used to calculate flow velocities in the saturated zone. Contaminant transport could be computed by the same methods as in the expected scenario.

4.14 Fracture Flow in the Calico Hills

Sequence numbers--6, 20, 21, 23, 53, 81.

Barriers affected--Sequences 20, 21, 23, and 81 affect only the Calico Hills nonwelded unit. Sequences 6 and 53 result from an increase in infiltration, which could affect all the other barriers.

Methods of analysis--Because most of these sequences affect only a single barrier, it may be found that there are no credible scenarios in which they play an important role. In that case, they need not be analyzed further.

The credibility of sequence 81, in which calcite is dissolved from veins in the Calico Hills, could be assessed by geochemical modeling to determine whether the moisture flux passing through the unit during the thermal period will be sufficient to dissolve out new flow paths. Additional data on the veins would probably have to be collected in the field for this work. It should be remembered that, even if it occurs, dissolution of calcite veins will not affect flow times unless the moisture flux rises above the matrix hydraulic conductivity.

Sequences 6 and 53, in which a perched water table forms below the repository and diverts flow toward existing fracture zones, can quite reasonably be expected to occur in the future and may represent a feature of the present system, as suggested by Montazer and Wilson (1984). Consequences of these sequences will have to be analyzed by methods similar to those used for the expected case; indeed, the expected case may bound them.

The other sequences involve undetected faults or dikes with low matrix hydraulic conductivity. For these sequences, geometric constraints and two-dimensional numerical modeling of moisture movement can be used to determine the fraction of total flux through the Calico Hills that moves through the fractures. The fractures could then be treated as a separate parallel pathway in contaminant-migration calculations.

4.15 New Discharge Points

Sequence numbers--33, 36.

Barriers affected--The only barrier on which there would be a direct negative effect would be the saturated zone. If the water table directly below the repository is lowered by pumping, travel times in the unsaturated zone would increase, which would have a positive effect on safety.

It should be noted that the flooding sequences discussed in Section 4.2 can create new discharges from the regional water-table aquifers. Because the repository is below the level of any potential discharge point much closer than 10 kilometers away, any new discharges from the regional water table other than wells imply flooding of the repository.

Methods of analysis--Analysis of flooding sequences is discussed in Section 4.2.

The irrigation mechanism in sequence 33 does not involve flooding of the repository. The plausibility of irrigation so close to the repository should first be investigated by evaluating the suitability of soils at nearby locations for agriculture. If these areas are suitable for irrigation, flow velocities should be calculated by inserting appropriate constant-discharge nodes in a two-dimensional ground-water flow model like the one developed by Czarnecki and Waddell (1984). These flow velocities can then be used to calculate contaminant travel times in the same way as for the expected case.

Scenarios involving mine dewatering (sequence 36) require that contamination reach the water table by some other mechanism by the time of the mine's operation. The probability of such scenarios is the probability that both mine dewatering and the other mechanism will occur. The likelihood of deep mining can be assessed from resource evaluations like that by Bell and Larson (1982).

It should be borne in mind that both mining in contaminated aquifers and use of contaminated ground water for irrigation are unlikely as long as the existence of the repository is known. Knowledge of the repository is likely to persist for a long time (Kaplan, 1982), but, as with the drilling scenarios discussed in Section 4.1, it is not reasonable to evaluate the probability quantitatively.

4.16 Faster Saturated Flow

Sequence numbers--3, 7, 17, 22, 34, 35, 37, 51, 62.

Barriers affected--Only the saturated zone will be affected directly. Sequences involving rises in the water table also imply faster flow in the unsaturated zone; they are discussed in Sections 4.2, 4.5, and 4.13.

Methods of analysis--Methods of calculating ground-water velocities in saturated flow systems are well developed. Models are already being calibrated for the Yucca Mountain flow system (Waddell, 1982; Rice, 1984; Czarnecki and Waddell, 1984). Changes in recharge, hydraulic conductivity, effective porosity, etc., which are posited by these failure sequences, may be inserted directly into these models to calculate flow velocities for different scenarios. Assessing the reliability of the calculated velocities may be a difficult problem, but it rests essentially on the correctness of the changed values of the hydraulic parameters and the accuracy of the model as a description of the current flow system.

Some of these sequences (3, 22, and 51) would require three-dimensional flow models even if only a two-dimensional model turns out to be needed for the expected case. Sequence 62, which is based on thermal convection, would require a model incorporating both water flow and heat transport for a full evaluation.

4.17 Acceleration of Pre-Existing Fracture Flow

Sequence numbers--18, 54, 80.

<u>Barriers affected</u>--Only the Topopah Spring welded unit will be significantly affected. Existing evidence argues strongly that there is at present no significant fracture flow in the Calico Hills nonwelded unit.

<u>Methods of analysis</u>--These sequences are speculative, so it is difficult to estimate the magnitude of any velocity increase. An upper bound could be obtained from tracer tests conducted on large saturated fractures, adjusted to unit gradient. With that velocity, existing models could be used in the same manner as for other fracture-flow sequences.

5 CONCLUSIONS AND RECOMMENDATIONS

The principal point of this report is to have systematically delineated the possible mechanisms involving disruptive events and processes by which radioactivity might be released over the long term from a high-level-waste repository located in unsaturated welded tuff at Yucca Mountain, Nevada. Such a repository would rely on six different, although not entirely independent, barriers to prevent escape of radioactivity. These barriers are the waste canister, fuel cladding, the resistance to dissolution of the spent fuel itself, and movement of released contaminants in three different hydrogeologic units: the unsaturated Topopah Spring welded unit, the unsaturated Calico Hills nonwelded unit, and the saturated tuff aquifer.

The 57 processes and events that might affect a repository included in a list published by the International Atomic Energy Agency, as well as one additional process identified more recently, were examined. Eighty-four different sequences were identified by which these processes and events could lead to failure of one or more barriers. Sequences that had similar consequences were grouped; the following 17 categories resulted:

- Direct release

- Repository flooding

- Colloid formation

- Increased water flux through the unsaturated zone

- Localized regions of high flux through the repository

- Water diverted toward the waste package

- Accelerated dissolution mechanisms

- Accelerated cladding-corrosion mechanisms

- Accelerated canister-corrosion mechanisms

- Canister breakage

- Fracture flow in the Topopah Spring welded unit without increased moisture flux

- Reduced sorption in the Topopah Spring welded unit

- Water-table rise above the Calico Hills nonwelded unit

- Fracture flow in the Calico Hills nonwelded unit

- New discharge points

- Faster flow in the saturated zone

- Acceleration of pre-existing fracture flow in the Topopah Spring welded unit

These categories should for the basis for further work in the analysis of disruptive event and process scenarios.

The amount of redundancy in the Yucca Mountain repository system is notable. Most of the more likely barrier-disruption sequences affect only one or a few of the barriers. The sequences in which little redundancy is apparent--principally direct release, saturation of the Calico Hills unit, and flooding of the repository--either are very unlikely or require direct human intrusion into the repository. Indeed, further analysis is likely to show most of them not to be credible.

In addition to the specific recommendations for further analysis made in Chapter 4, several general suggestions for the future direction of the Yucca Mountain performance-assessment program can be made. These are the following:

- The saturated zone has a considerable potential to provide a redundant barrier if the unsaturated-flow barriers are disrupted. If, as is likely, substantial matrix diffusion occurs, the saturated zone will be quite effective in preventing release of radioactivity within 10,000 years. Some effort should be devoted to developing a better understanding of the saturated flow system during site characterization, and especially to measuring matrix diffusion.

- More needs to be known about whether radioactive colloids will play a substantial role in migration of radioactivity away from a repository. Research on the physics of colloid movement and filtration effects may be more directly useful in bounding the importance of colloids than detailed study of the chemistry of colloid formation.

- Localized corrosion mechanisms are much more likely than uniform corrosion to lead to unacceptable breaches of waste canisters or cladding. Future research should concentrate on these types of corrosion. Especially needed is work on stress-corrosion cracking and on corrosion of partially wetted metal surfaces.

- More work on the corrosion of fuel cladding may show that the cladding is a valuable redundant barrier in the system.

- More work on understanding the extent to which the air gap between the waste packages and the rock impedes water contact with the waste may show this effect to be a valuable redundant barrier.

- Research on the chemical properties of the unsaturated zone should concentrate on the case in which water flows through fractures. This emphasis should be retained even if matrix flow is confirmed as the current mechanism of moisture movement, because matrix flow in the Yucca Mountain unsaturated zone is so slow that sorption is not needed to provide acceptable performance unless there is fracture flow.

APPENDIX A

Table of Barrier-Failure Sequences

This appendix consists of a table listing the barrier-failure sequences identifed in Chapter 2. Some of the sequence descriptions are abridged versions of those presented in Chapter 2.

Climate Change

1. An increase in infiltration due to climate change at the repository site increases the unsaturated water flux through the repository.

2. An increase in recharge due to climate change raises the water table beneath the repository above the top of the Calico Hills nonwelded tuff unit.

3. A higher water table short-circuits a flow barrier in the saturated zone, changing the pattern of flow.

4. Regionally higher water tables create discharge points closer to the repository, reducing the distance to the accessible environment. The rise in the regional water table floods the repository.

5. Perched water develops above the repository, diverting downward flow through the repository into localized zones.

6. Perched water develops at the base of the Topopah Spring welded unit. Flow through the Calico Hills unit is diverted into fracture zones draining the perched water table.

Stream Erosion

7. Entrenchment of the Amargosa River at Alkali Flat lowers base levels and increases regional gradients. Regional hydraulic relations are such that water-table lowering at Yucca Mountain is insignificant, but increases in ground-water velocity are significant.

8. Beds of intermittent streams now resting on the Tiva Canyon welded tuff unit erode through to the underlying nonwelded unit. These washes form a barrier to lateral flow in the Tiva Canyon and divert flow downward. Regions of high flux are formed below them.

Flooding

9. Flooding of the washes on Yucca Mountain is a major source of infiltration, and zones of higher moisture flux exist permanently or seasonally below washes. One or more of these zones is not detected during site characterization.

10. Occasional major floods provide sufficient infiltration to overcome the capillary barrier that usually diverts flow laterally, creating temporary wetter zones beneath the washes.

11. Most percolation through the deeper unsaturated portions of Yucca Mountain occurs following major precipitation events whose recurrence interval is tens, hundreds, or thousands of years. After future events, there are periods of tens to hundreds of years during which percolation through the unsaturated zone is increased over the present relatively dry conditions. Fracture flow then occurs in the Topopah Spring unit and perhaps other hydrogeologic units between the repository and the water table.

Faulting and Seismicity

12. Movement of a new or existing fault shears canisters along the line of the fault. The same fault also creates a "trap" for moisture moving laterally through the Tiva Canyon welded unit, and so the sheared canisters are placed in a region of enhanced downward moisture flux.

13. Fracture dilation along a new or existing fault creates zones of enhanced permeability in the Calico Hills and Paintbrush nonwelded units. Erosion of an arroyo at the surface and increased hydraulic conductivity of the Paintbrush unit create a zone of increased percolation along the fault. Moisture moves through fractures along the fault.

14. The downdip side of a new or existing fault moves up. The fault thus forms a "trap" for laterally moving moisture in the Tiva Canyon welded unit. A new region of enhanced flux through the Topopah Spring unit is created.

15. Fracturing along a newly mobilized fault creates a permeable pathway through the flow barrier north of the repository block. The magnitude of the resulting change in the flow system is sufficient to raise the water table under the repository to the top of the Calico Hills nonwelded unit.

16. As in the previous scenario, fault-caused fracturing breaches the flow barrier north of the repository block. Flow is blocked by another barrier, not apparent from the current head distribution, and the resulting rise in water table floods the repository. The water passing through the repository discharges through springs in Fortymile Wash.

Geochemical Changes

17. Precipitation of zeolites or other minerals in the saturated zone reduces effective porosity without significantly improving the sorptive properties of the rocks.

18. Fracture flow occurs in the unsaturated zone at current percolation rates. Precipitation or alteration of minerals blocks the small-aperture fractures and diverts the flow into larger fractures, increasing the water velocity.

Undetected Faults and Shear Zones

19. A wet zone below a minor fault through the Tiva Canyon lower contact escapes detection during repository construction, and waste is emplaced in it.

20. An undetected major fault dips below the repository. The fault has greater permeability than surrounding unfaulted rock, and enhanced moisture flow along it passes through the Calico Hills nonwelded unit in fractures.

21. An undetected major fault dips below the repository. Because of the formation of fault gouge, matrix hydraulic conductivity in the fault is less than the moisture flux, and so moisture flows through the Calico Hills nonwelded unit along fractures in or just above the fault.

22. An undetected fault provides a path for water movement from the tuff aquifer beneath the western portion of the repository to an underlying carbonate aquifer.

Undetected Dikes

23. An undetected dike passing through the Calico Hills nonwelded unit beneath the repository has very low matrix permeability but fairly high fracture permeability. Moisture infiltrating along the dike moves through fractures.

Extrusive Magmatic Activity

24. A basaltic volcano erupts through the repository. The volcano is fed through a dike; waste canisters within the dike mix with the magma, and their contents are erupted.

Faulty Waste Emplacement

25. Canisters are placed by mistake in wet zones.

26. Drains installed to divert water around canisters are improperly built or omitted altogether over some canisters.

27. Canisters are left lying on the floor of repository drifts. These canisters have poorer heat removal than those properly emplaced, and their increased horizontal cross-section raises the amount of water they intercept. Water drips on the canisters and corrodes them even while their temperatures are well above 95° C.

28. Canisters are placed closer together than planned. As a result, temperatures inside the packages are higher than anticipated and corrosion of fuel cladding is accelerated.

29. Some waste canisters are manufactured so improperly that they fail early.

30. Some waste canisters are punctured or abraded during emplacement.

Irrigation

31. Irrigation in Midway Valley increases the moisture flux through the repository.

Intentional Ground-Water Recharge or Withdrawal

32. Water is collected in covered cisterns above the repository to enhance ground-water recharge.

33. Irrigation wells are drilled in Midway Valley.

34. Irrigation wells are drilled in Crater Flat or Jackass Flats.

35. Pumping rates increase in the presently irrigated area around the town of Amargosa Valley. The water table is significantly drawn down, and the hydraulic gradient increases.

36. Mine dewatering is carried out directly below the repository. The saturated zone is eliminated as a barrier.

Large-Scale Alterations of Hydrology

37. An active management scheme is introduced for the Alkali Flat-Furnace Creek Ranch ground-water basin, by which hydraulic gradients in the saturated zone beneath the repository are increased.

Undiscovered Boreholes

38. A horizontally emplaced waste canister lies in the trace of an old undiscovered borehole. Moisture conditions are wetter than now thought, and water flows in fractures in the old borehole.

Undiscovered Mine Shafts

39. An old prospect in a wash retains water after floods, and therefore is a source of enhanced infiltration. The wet zone beneath it is not detected during repository construction, and waste is emplaced in it.

Exploratory Drilling

40. Exploratory drillers intercept a waste canister and bring waste up with the cuttings.

41. Water introduced into the unsaturated zone as drilling fluid by exploratory drillers drains downward, through the repository.

42. An exploratory borehole creates a pathway for preferential flow through the upper nonwelded unit, and a wetter zone develops beneath in the Topopah Spring welded unit.

43. Surfactants introduced into unsaturated rock by drilling fluids shift its characteristic curve, draining smaller pores around the borehole. Water introduced by subsequent infiltration events acts as though air were the wetting phase and flows through large pores and fractures.

Resource Mining

44. Builders of a mine shaft intercept a waste canister and bring radioactive waste up with the mine waste.

45. Water introduced into the unsaturated zone for mining above the repository drains downward through the repository.

46. A mine shaft creates a pathway for preferential flow through the upper nonwelded unit, and a wetter zone develops beneath in the Topopah Spring welded unit.

47. Surfactants introduced into unsaturated rock by drilling fluids shift its characteristic curve, draining smaller pores around the mine. Water introduced by subsequent infiltration events acts as though air were the wetting phase and flows through large pores and fractures.

Climate Control

48. An increase in recharge at the repository site due to artificial climate change increases the unsaturated water flux through the repository.

49. An increase in recharge due to climate modification raises the water table beneath the repository above the top of the Calico Hills nonwelded tuff unit and induces fracture flow in the welded Topopah Spring unit.

50. Recharge induced by large-scale climate modification raises the regional water table sufficiently to flood the repository.

51. A higher water table due to climate modification short-circuits a flow barrier in the saturated zone, changing the pattern of flow.

52. Perched water develops above the repository because of climate-modification-induced recharge, diverting downward flow through the repository into localized zones.

53. An increase in recharge due to climate control causes perched water to develop at the base of the Topopah Spring welded unit. Flow through the Calico Hills nonwelded unit is diverted into fracture zones draining the perched water table.

Differential Elastic Response to Heating

54. Thermal expansion closes most fractures near the repository. Pre-existing fracture percolation is diverted into fractures of larger aperture.

55. Differential thermal expansion of surrounding rocks stresses canisters, leading to stress-corrosion cracking.

56. Differential thermal expansion of surrounding rocks creates stresses that shear canisters.

57. Rock movements driven by thermal expansion of underlying units open fractures through the Paintbrush nonwelded unit. This creates local zones of increased flux through the unsaturated units below.

Nonelastic Response to Heating

58. Thermally induced fracturing of rocks immediately surrounding waste canisters creates capillary barriers to movement of moisture between blocks of the rock matrix. The matrix is locally saturated, forcing flow out into the fractures and resulting in film flow or droplet impact on waste packages. The result is accelerated localized corrosion and waste dissolution.

Temperature-Driven Fluid Migration

59. Water accumulates above a repository during the thermal period because of evaporation and condensation. When gravity-driven flow resumes, a large volume of water contacts canisters, and flow goes through fractures.

60. Emplacement of waste in the floor of repository drifts creates a large thermal gradient across the drifts. Moisture condenses on the roof and drips onto canisters, accelerating corrosion.

61. Temperature inhomogeneities in the repository lead to localized accumulation of moisture above it. Wet zones form below the areas of moisture accumulation.

62. A thermal convection cell arises in the saturated zone beneath the repository. The thermally driven outward water flow in the upper portion of the tuff aquifer increases ground-water velocities.

Local Mechanical Fracturing

63. Rockbursts propel rocks into waste packages and puncture the canisters.

Corrosion

64. Water drips or wicks onto canisters at specific locations, leading to buildup of brine deposits on small previously stressed areas. These areas are focuses of localized attack.

65. Water drips or wicks onto canisters at specific locations, leading to buildup of brine deposits on small areas that happen to have previously been stressed. Stress-corrosion cracking ensues.

66. The canister material is subject to stress-corrosion cracking, but the initiation time is too long to be detected in tests. Canisters fail by this mechanism a few decades after the repository has been sealed.

67. Canisters are sensitized by long-term storage at moderately hot temperatures in the repository. Stress-corrosion cracking (or perhaps intergranular corrosion) ensues in a stressed zone.

68. Zircaloy cladding is subject to stress-corrosion cracking at repository temperatures, but initiation times are too long for detection in in-reactor service or in the repository testing program.

69. After canister breach, colloids of corrosion products sorb normally higly retarded radionuclides and carry them away unretarded.

Chemical Reaction of Waste Package With Rock

70. Water dripping or running over waste contains ions that precipitate uranium. The precipitation reaction removes uranium from solution and increases the rate of fuel dissolution.

71. Waste and rock are placed in close juxtaposition by mechanical failure of emplacement holes or drifts, or by small movements on faults. Reactions between uranium, rock minerals, and water in contact with both precipitate uranium, leading the spent fuel to dissolve more rapidly than if constrained by the equilibrium solubility of uranium.

72. The high dissolved-silica content of natural waters entering the repository causes rapid corrosion of Zircaloy fuel cladding.

73. Colloids are formed from the rock by alteration under thermal, mechanical, and chemical stresses. Normally well-retarded radioelements such as plutonium and americium sorb to the colloids.

74. Waste-contaminated water reacts with rock, and colloid phases of minerals containing radioelements are formed by coprecipitation. The colloids are transported with little or no retardation.

Geochemical Alteration

75. During the period of heating of rocks around the repository, minerals adjacent to the residual water-bearing pores are altered to clays. These clays clog the pores. When the repository cools, water flows through fractures.

76. During the thermal period, zeolite minerals in fracture fillings are altered to less sorptive phases.

77. Waters moving away from the hot region around the repository precipitate minerals derived from dissolved constituents of tuff and cements used in repository construction. These minerals clog pores and divert subsequent flows into fractures.

78. Evaporation of ground water in the hot zone near the repository horizon leaves precipitates that plug pores. As a result, when gravity-driven flow resumes, water near the repository is diverted into fractures. Initially, there is a pulse of corrosive brine.

79. Evaporation of ground water in the hot zone near the repository horizon leaves precipitates. When gravity-driven flow resumes, the precipitates redissolve, and after a short period of fracture flow, the flow returns to the matrix. There is a considerable period of flow of corrosion brines with elevated dissolved solids.

80. There is fracture flow in the Topopah Spring welded unit even under undisturbed conditions. Chemical reactions induced by repository heat plug smaller-aperture fractures. After the thermal pulse ends, percolation is diverted into larger fractures.

81. Water passing through the warm region around the repository is depleted of calcite by temperature-induced precipitation. Below the repository, the calcite-poor water dissolves out calcite veins in the Calico Hills nonwelded unit.

Microbial Activity

82. Microbial activity accelerates canister corrosion.

83. Microbial activity accelerates cladding corrosion.

84. Radionuclides are incorporated into microorganisms or sorbed on their surfaces. Waste dissolution is accelerated. The nuclides taken up by microorganisms are unaffected by chemical sorption or matrix diffusion.

APPENDIX B

Information Relevant to the Reference Information Base

B-1 Sources of Data Used in the Report

All numerical and graphical data used in this report were adopted or taken directly from publications cited in appropriate places of the text. These publications are listed in the reference section at the end of the report.

B-2 Data Recommended for Inclusion Into the Reference Information Base

The 84 barrier-failure sequences listed in Appendix A are recommended for inclusion in the Reference Information Base.

B-3 Data Recommended for Inclusion Into the Tuff Data Base

None.

REFERENCES

Avogadro, A., and G. de Marsily, "The Role of Colloids in Nuclear Waste Disposal," in G.L. McVay, ed., Scientific Basis for Nuclear Waste Management VII, North Holland, New York, NY, 1984, pp. 495-505.

Bell, E. J., and L. T. Larson, "Overview of Energy and Mineral Resources for the Nevada Nuclear Waste Storage Investigations, Nevada Test Site, Nye County, Nevada," Las Vegas, Nevada; U.S. Department of Energy, Report NVO-250, September 1982.

Braithwaite, J. W., amd F. B. Nimick, Effect of Host-Rock Dissolution and Precipitation on Permeability in a Nuclear Waste Repository in Tuff, SAND84-0192, Albuquerque, NM: Sandia National Laboratories, 1984.

Burkholder, H. C., "Waste Isolation Performance Assessment--A Status Report," in C.J.M. Northrup, ed., Scientific Basis for Nuclear Waste Management, v. 2, Plenum, New York, NY, 1980, p. 689.

Byerlee, J., C. Morrow, and D. Moore, Permeability and Pore-Fluid Chemistry of the Bullfrog Tuff in a Temperature Gradient: Summary of Results, Open-File Report 83-475, Denver, CO: U.S. Geological Survey, 1983.

Claassen, H. C., Sources and Mechanisms of Recharge for Ground Water in the West-Central Amargosa Desert, Nevada--A Geochemical Interpretation, Open-File Report 83-542, Denver, CO: U.S. Geological Survey, 1983.

Craig, R. W., and J. H. Robison, Geohydrology of Rocks Penetrated by Test Well UE-25p#1, Yucca Mountain Area, Nye County, Nevada, Water-Resources Investigations Report 84-4248, Denver, CO: U.S. Geological Survey, 1984.

Crowe, B. M., M. E. Johnson, and R. J. Beckman, "Calculation of the Probability of Volcanic Disruption of a High-Level Radioactive Waste Repository Within Southern Nevada, USA," Radioactive Waste Management and the Nuclear Fuel Cycle, v. 3, pp. 167-190, 1982.

Czarnecki, J. B., Predicted Effects of Climatic Changes on Water Table Position Beneath Yucca Mountain, Nevada Test Site, Water Resources Investigations Report 84-4344, Denver, CO: U.S. Geological Survey, 1984.

Czarnecki, J. B., and R. K. Waddell, Finite-Element Simulation of Ground-Water Flow in the Vicinity of Yucca Mountain, Nevada-California, Water-Resources Investigations Report 84-4349, Denver, CO: U.S. Geological Survey, 1984.

Dayal, R., B. S. Lee, R. J. Wilke, K. J. Swyler, P. Soo, T. M. Ahn, N. S. McIntyre, and E. Veakis, Nuclear Waste Management Technical Support in the Development of Nuclear Waste Form Criteria for the NRC, Task 1, Waste Package Overview, Report NUREG/CR-2333, v. 1, Washington, D.C.: U.S. Nuclear Regulatory Commission, 1982.

de Marsily, G., "An Overview of Coupled Processes With Emphasis in Geohydrology," presented to International Symposium on Coupled Processes Affecting the Performance of a Nuclear Waste Repository, Berkeley, CA, September 18-20, 1985.

DOE, Draft Environmental Assessment, Yucca Mountain Site Nevada Research and Development Area, Nevada, Report DOE/RW-0012, Washington, D.C.: U.S. Department of Energy, 1984.

EPA, "Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes; Final Rule, 40 CFR Part 191," Federal Register, v. 50, Washington, D.C.: U.S. Printing Office, 1985, pp. 38066-38089.

Fernandez, J. A., and M. D. Freshley, Repository Sealing Concepts for the Nevada Nuclear Waste Storage Investigations Project, SAND83-1778, Albuquerque, NM: Sandia National Laboratories, 1984.

Freeze, R. A., and J. A. Cherry, Groundwater, Englewood Cliffs, NJ: Prentice-Hall, 1979.

Gause, E., and P. Soo, Review of DOE Waste Package Program, Subtask 1.1--National Waste Package Program, April 1984 - September 1984, Report NUREG/CR-2482, v. 7, Washington, D.C.: U.S. Nuclear Regulatory Commission, 1985.

Gregg, D. W., and W. C. O'Neal, Initial Specifications for Nuclear Waste Package External Dimensions and Minerals, Report UCID-19926, Livermore, CA: Lawrence Livermore Laboratory, 1983.

Hoover, D. L., W. C. Swadley, and A. J. Gordon, Correlation Characteristics of Surficial Deposits With a Description of the Surficial Stratigraphy in the Nevada Test Site Region, Open-File Report 81-512, Denver, CO: U.S. Geological Survey, 1981.

Hunt, J. R., L. M. McDowell-Boyer, and N. Sitar, "Colloid Migration in Porous Media," presented to International Symposium on Coupled Processes Affecting the Performance of a Nuclear Waste Repository, Berkeley, CA, September 18-20, 1985.

Hunter, R. L., G. E. Barr, and F. W. Bingham, Preliminary Scenarios for Consequence Assessments of Radioactive-Waste Repositories at the Nevada Test Site, SAND82-0426, Albuquerque, NM: Sandia National Laboratories, 1982.

Hunter, R.L., G.E. Barr, and F.W. Bingham, Scenarios for Consequence Assessments of Radioactive-Waste Repositories at Yucca Mountain, Nevada Test Site, SAND82-1277, Albuquerque, NM: Sandia National Laboratories, 1983.

IAEA, Concepts and Examples of Safety Analysis for Radioactive Waste Repositories in Continental Geological Formations, Safety Series No. 58, Vienna, Austria: International Atomic Energy Agency, 1983.

REFERENCES (continued)

Johnstone, J. K., R. R. Peters, and P. F. Gnirk, Unit Evaluation at Yucca Mountain, Nevada Test Site: Summary Report and Recommendation, SAND82-0372, Albuquerque, NM: Sandia National Laboratories, 1984.

Kaplan, M. F., Archaeological Data as a Basis for Repository Marker Design, Office of Nuclear Waste Isolation, Report ONWI-354, Columbus, OH: Battelle Memorial Institute, 1982.

KBS, Kaernbraenslecykelns Slugsteg, Foerglasat Avfall Fraan Upparbetning, Swedish Nuclear Fuel Supply Co., 1977.

KBS, Final Storage of Spent Nuclear Fuel - KBS-3, Swedish Nuclear Fuel Supply Co., 1983.

Kocher, D. C., Radioactive Decay Data Tables, Report DOE/TIC-11026, Washington, D.C.: U.S. Department of Energy, 1981.

Koplik, C. M., M. F. Kaplan, and B. Ross, "The Safety of Repositories for Highly Radioactive Wastes," Rev. Mod. Phys., v. 54, pp. 269-310, 1982.

Logan, S. E., R. L. Link, H. S. Ng, F. A. Rockenbach, and K. J. Hong (Link is listed as first author on the report cover), Parametric Studies of Radiological Consequences of Basaltic Volcanism, SAND81-2375, Albuquerque, NM: Sandia National Laboratories, 1982.

McCright, R. D., H. Weiss, M. C. Juhas, and R. W. Logan, Selection of Candidate Canister Materials for High-Level Nuclear Waste Containment in a Tuff Repository, Preprint UCRL-89988, Livermore, CA: Lawrence Livermore Laboratory, 1983.

Montazer, P., and W. E. Wilson, Conceptual Hydrologic Model of Flow in the Unsaturated Zone, Yucca Mountain, Nevada, Water-Resources Investigations Report 84-4345, Lakewood, CO: U.S. Geological Survey, 1984.

Montazer, P., and W. E. Wilson, "Conceptual Model of Fluid Flow in Unsaturated Fractured Tuffs," presented to American Geophysical Union, Spring Meeting, Baltimore, MD, May 1985.

NRC, "Disposal of High-Level Radioactive Wastes in Geologic Repositories," Code of Federal Regulations, Title 10, Part 60, Washington, D.C.: U.S. Government Printing Office, 1983.

NRC, NRC Comments on DOE Draft Environmental Assessment for the Yucca Mountain Site, Washington, D.C.: U.S. Nuclear Regulatory Commission, March 20, 1985.

O'Neal, W. C., L. B. Ballou, D. W. Gregg, and E. W. Russell, "Nuclear Waste Package Design for the Vados Zone in Tuff," in R.G. Post, ed., Waste Management '84, v. 1, Tucson, AZ: Arizona Board of Regents, 1984, pp. 547-551.

Rice, W. A., Preliminary Two-Dimensional Regional Hydrologic Model of the Nevada Test Site and Vicinity, SAND83-7466, Albuquerque, NM: Sandia National Laboratories, 1984.

Roseboom, E. H., Jr., Disposal of High-Level Nuclear Waste Above the Water Table in Arid Regions, Circular 903, U.S. Geological Survey, 1983.

Rush, F. E., W. Thordarson, and D. G. Pyles, Geohydrology of Test Well USW H-1, Yucca Mountain, Nye County, Nevada, Water-Resources Investigations Report 84-4032, Denver, CO: U.S. Geological Survey, 1984.

Scott, R. B., and J. Bonk, Preliminary Geologic Map of Yucca Mountain, With Geologic Sections, Nye County, Nevada, Open-File Report 84-494, Denver, CO: U.S. Geological Survey, 1984.

Scott, R. B., and R. W. Spengler, S. Diehl, A. R. Lappin, and M. P. Chornak, "Geologic Character of Tuffs in the Unsaturated Zone at Yucca Mountain, Southern Nevada," in J.W. Mercer, P.S. Rao, and I.W. Marine, eds., Role of the Unsaturated Zone in Radioactive and Hazardous Waste Disposal, Ann Arbor, MI., Ann Arbor Science Publishers, 1983, pp. 289-335.

Scott, R. B., G. D. Bath, V. J. Flanigan, D. B. Hoover, J. G. Rosenbaum, and R. W. Spengler, Geological and Geophysical Evidence of Structures in Northwest-Trending Washes, Yucca Mountain, Southern Nevada, and Their Possible Significance to a Nuclear Waste Repository in the Unsaturated Zone, Open-File Report 84-567, Denver, CO: U.S. Geological Survey, 1984.

Sinnock, S., Y. T. Lin, and J. P. Brannen, Preliminary Bounds on the Expected Postclosure Performance of the Yucca Mountain Repository Site, Southern Nevada, SAND84-1492, Albuquerque, NM: Sandia National Laboratories, Report 1984.

Smith, C. B., D. J. Egan, Jr., W. A. Williams, J. M. Grunlke, C. -Y. Hung, and B. L. Serini, Population Risks From Disposal of High-Level Radioactive Wastes in Geologic Repositories, Report EPA-520/3-80-006, Washington, D.C.: U.S. Environmental Protection Agency, 1982.

Smyth, J. R., "Zeolite Stability Constraints on Radioactive Waste Isolation in Zeolite-Bearing Volcanic Rocks," J. Geology, v., 90, pp. 195-201, 1982.

Spaulding, W. G., Vegetation and Climates of the Last 45,000 Years in the Vicinity of the Nevada Test Site, South-Central Nevada, Open-File Report 83-535, Lakewood, CO: U.S. Geological Survey, 1983.

Squires, R. R., and R. L. Young, Flood Potential of Fortymile Wash and its Principal Southwestern Tributaries, Nevada Test Site, Southern Nevada, Water-Resources Investigations Report 83-4001, Carson City, NV: U.S. Geological Survey, 1984.

Swadley, W. C., and D. L. Hoover, Geology of Faults Exposed in Trenches in Crater Flat, Nye County, Nevada, Open-File Report 83-608, Denver, CO: U.S. Geological Survey, 1983.

Thordarson, W., Perched Ground Water in Zeolitized-Bedded Tuff, Rainier Mesa and Vicinity, Nevada Test Site, Nevada, Report TEI-862, Denver, CO: U.S. Geological Survey, 1965.

Thordarson, W., F. E. Rush, and S. J. Waddell, Geohydrology of Test Well USW H-3, Yucca Mountain, Nye County, Nevada, Water Resources Investigations Report 84-4272, Lakewood, CO: U.S. Geological Survey, 1985.

Travis, B. J., and H. E. Nuttall, "Analysis of Colloid Transport," presented to International Symposium on Coupled Processes Affecting the Performance of a Nuclear Waste Repository, Berkeley, CA; September 18-20, 1985.

Tsang, C.-F., and D. C. Mangold, eds., Panel Report on Coupled Thermo-Mechanical-Hydro-Chemical Processes Associated With a Nuclear Waste Repository, Report LBL-18250, Livermore, CA: Lawrence Berkeley Laboratory, July 1984.

USGS, A Summary of Geologic Studies of a Potential High-Level Radioactive Waste Repository Site at Yucca Mountain, Southern Nye County, Nevada, Open-File Report 84-792, Menlo Park, CA: U.S. Geological Survey, 1984.

Waddell, R. K., Two-Dimensional, Steady-State Model of Ground-Water Flow, Nevada Test Site and Vicinity, Nevada-California, Water Resources Investigations Report 82-4085, Denver, CO: U.S. Geological Survey, 1982.

Waddell, R. K., J. H. Robison, and R. K. Blankennagel, Hydrology of Yucca Mountain and Vicinity, Nevada-California--Investigative Results Through Mid-1983, Water Resources Investigations Report 84-4267, Denver, CO: U.S. Geological Survey, 1984.

West, J. M., N. Christofi, and I. G. McKinley, "An Overview of Recent Microbiological Research Relevant to the Geological Disposal of Nuclear Waste," Radioactive Waste Management and the Nuclear Fuel Cycle, v. 6, pp. 79-95, 1985.

West, J. M., and I. G. McKinley, "The Geomicrobiology of Nuclear Waste Disposal," in G. L. McVay, ed., Scientific Basis for Nuclear Waste Mangement VII, North Holland, New York, NY, 1984, pp. 487-494.

Winograd, I. J., "Radioactive Waste Storage in the Arid Zone," Eos Trans. AGU, v. 55, 1974, pp. 884-894.

Winograd, I. J., and G. C. Doty, Paleohydrology of the Southern Great Basin, With Special Reference to Water Table Fluctuations Beneath the Nevada Test Site During the Late (?) Pleistocene, Open-File Report 80-569, Reston, VA: U.S. Geological Survey, 1980.

Winograd, I. J., B. J. Szabo, T. B. Coplen, A. C. Riggs, and P. T. Kolesar, "Two-Million-Year Record of Deuterium Depletion in Great Basin Ground Waters," Science, v. 227, pp. 519-522, 1985.

Yeh, T.-C. J., L. W. Gelhar, and A. L. Gutjahr, "Stochastic Analysis of Unsaturated Flow in Heterogeneous Soils, 1, Statistically Isotropic Media," Water Resour. Res., v. 21, pp. 447-456, 1985a.

Yeh, T.-C. J., L. W. Gelhar, and A. L. Gutjahr, "Stochastic Analysis of Unsaturated Flow in Heterogeneous Soils, 2, Statistically Anisotropic Media With Variable Alpha," Water Resour. Res., v. 21, pp. 457-464, 1985b.

Yeh, T.-C. J., L. W. Gelhar, and A. L. Gutjahr, "Stochastic Analysis of Unsaturated Flow in Heterogeneous Soils, 3, Observations and Applications," Water Resour. Res., v. 21, pp. 465-472, 1985c.

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