Viability Assessment of a Repository at Yucca Mountain

# Introduction and Site Characteristics

U.S. Department of Energy

Office of Civilian Radioactive Waste Management

Volume 1

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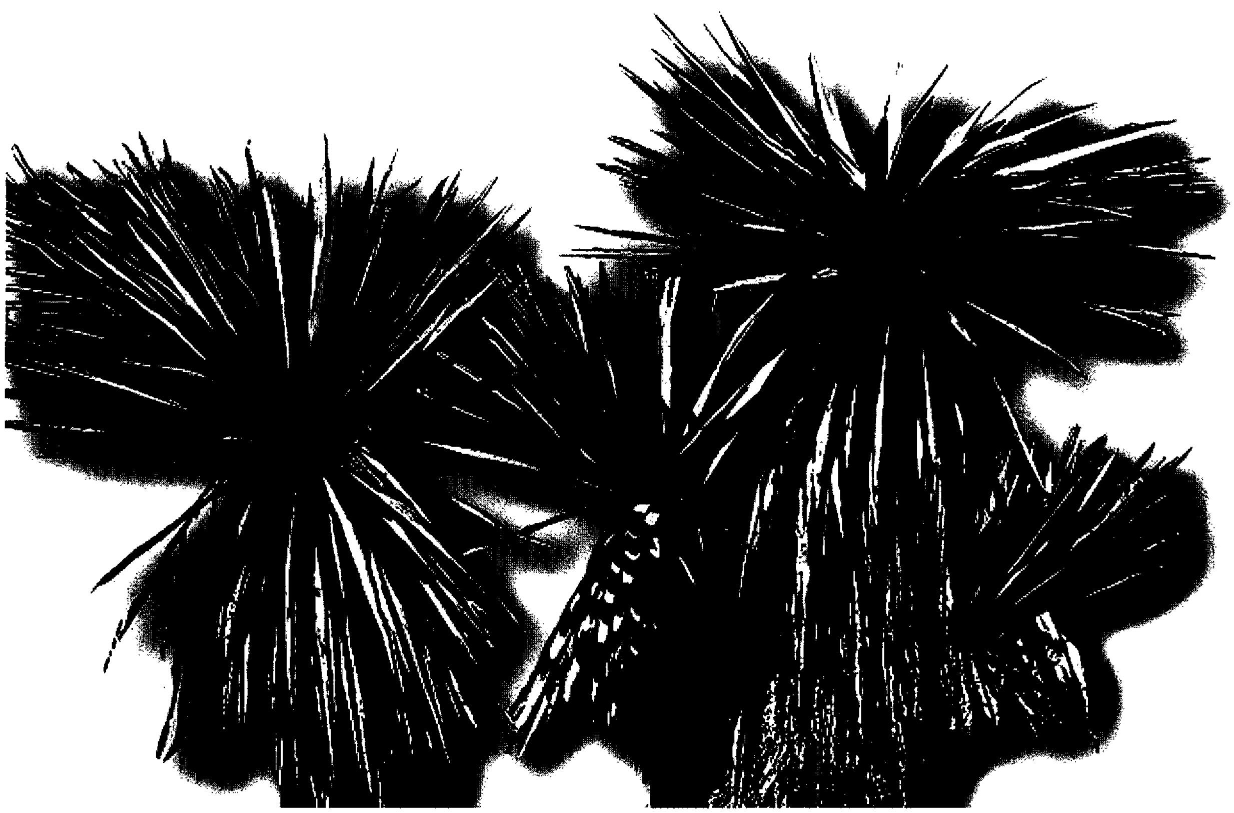
# Viability Assessment
# of a Repository at Yucca Mountain

## Volume 1: Introduction and Site Characteristics

**December 1998**



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# ACRONYMS

| | |
|---|---|
| AEC | U.S. Atomic Energy Commission |
| ASTM | American Society for Testing and Materials |
| CFR | Code of Federal Regulations |
| CRWMS | Civilian Radioactive Waste Management System |
| DOE | U.S. Department of Energy |
| ECRB | Enhanced Characterization of the Repository Block |
| EIS | Environmental Impact Statement |
| EPA | U.S. Environmental Protection Agency |
| ERDA | U.S. Energy Research and Development Administration |
| LA | License Application |
| M&O | Management and Operating Contractor |
| NRC | Nuclear Regulatory Commission |
| OCRWM | Office of Civilian Radioactive Waste Management |
| TSPA | Total System Performance Assessment |
| USGS | U.S. Geological Survey |
| VA | Viability Assessment |
| YMP | Yucca Mountain Site Characterization Project |
| YMSCO | Yucca Mountain Site Characterization Office |

**Measurements**

| | |
|---|---|
| Btu | British thermal unit |
| cm | centimeter |
| Eh | redox potential |
| ft | foot |
| g | gram |
| in. | inch |
| kg | kilogram |
| km | kilometer |
| kPa | kilopascal |
| kV | kilovolt |
| kVA | kilovolt-ampere |

| | |
|---|---|
| lin ft | linear feet |
| m | meter |
| mL | milliliter |
| mm | millimeter |
| MPa | megapascal |
| MTHM | metric tons of heavy metal |
| MTU | metric tons of uranium |
| MVA | megavolt-ampere |
| nm | nanometer |
| pH | hydrogen-ion concentration notation |
| ppm | parts per million |
| ppmv | parts per million by volume |
| psi | pounds per square inch |
| wt | weight |

# 1. INTRODUCTION TO THE VIABILITY ASSESSMENT

Since 1983, under the Nuclear Waste Policy Act of 1982, the U.S. Department of Energy (DOE) has been investigating a site at Yucca Mountain, in Nevada, to determine whether it is suitable for development as the nation's first repository for permanent geologic disposal of spent nuclear fuel and high-level radioactive waste.

Based on the scientific study of Yucca Mountain, DOE believes that the site remains promising for development as a geologic repository. However, uncertainties remain about key natural processes, the preliminary design, and how the site and design would interact. The Secretary of Energy has not yet decided whether to recommend the site to the President of the United States. That decision is scheduled for 2001 after issuance of a final environmental impact statement (EIS) and evaluation of the suitability of the site for development as a geologic repository.

DOE will continue to improve the repository design to provide extra margins of safety and will conduct additional research and testing to reduce remaining uncertainties. The EIS, which will accompany any site recommendation and license application (LA), will be prepared, published for public comment in 1999, and finalized in 2000. DOE will evaluate the suitability of the site for development as a repository in 2001. After considering the final EIS, the suitability evaluation, the views and comments of any state or affected Indian tribe, the comments of the U.S. Nuclear Regulatory Commission (NRC), and other information, the Secretary of Energy will decide whether or not to recommend the site to the President. The President, in turn, will decide whether or not to recommend the site to the U.S. Congress.

If the President does recommend the site to Congress, the State of Nevada may disapprove the recommendation. A notice of disapproval may be overruled by a joint resolution of Congress. If the presidential recommendation stands and the site designation is permitted to take effect, DOE plans to submit an LA to NRC in 2002. The NRC licensing proceeding is expected to take three to four years, with construction beginning in 2005, leading to the start of repository operations in 2010.

The schedule for repository development is shown in Figure 1-1 and is discussed further in Section 1.9.

## 1.1 PURPOSE AND SCOPE OF THE VIABILITY ASSESSMENT

Since May 1996, under its draft *Civilian Radioactive Waste Management Program Plan* (DOE 1996), DOE has been carrying out a 5-year program of work to support the decision in 2001 by the Secretary of Energy on whether or not to recommend the site to the President. Part of this program was to address major unresolved technical issues and to complete an assessment of the viability of the Yucca Mountain site by 1998. Affirming the DOE plans, Congress directed DOE in the 1997 Energy and Water Development Appropriations Act to provide a viability assessment of the Yucca Mountain site to Congress and the President. This Viability Assessment (VA) document is the DOE report to Congress and the President. They are expected to use the VA to make an informed decision about program direction and funding.

Drawing on 15 years of scientific investigation and design work at Yucca Mountain, the VA summarizes a large technical basis of field investigations, laboratory tests, models, analyses, and engineering, described in cited references. The VA identifies the major uncertainties relevant to the technical defensibility of DOE analyses and designs, the DOE approach to managing these uncertainties, and the status of work toward the site recommendation and LA. The VA also identifies DOE plans for the remaining work, and the estimated costs of completing an LA and constructing and operating a repository. The attention to uncertainties is important because DOE must evaluate how the repository will perform during the next 10,000 years or longer. Uncertainties exist because of variability in the natural (geologic and hydro-

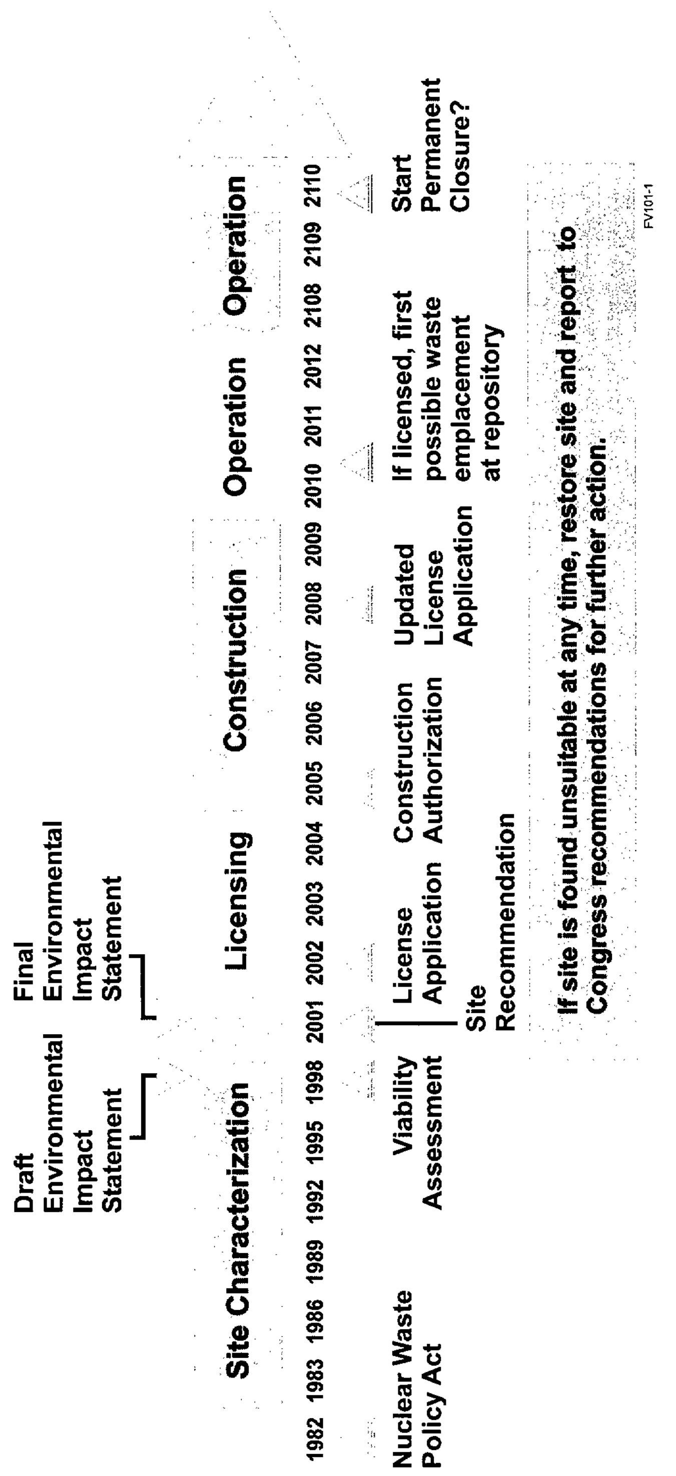



Figure 1-1. Repository Milestones

logic) systems at Yucca Mountain and because of imperfect scientific understanding of the natural processes that might affect the repository system.

The VA is organized as follows:

- Volume 1, "Introduction and Site Characteristics," includes a high-level summary of the results of the VA and some additional background information. (The overview is bound separately.) Section 1 of Volume 1 provides introductory information about the types of waste that are destined for geologic disposal, the challenges posed by geologic disposal, a history of efforts to site a geologic repository in the United States, a brief description of how DOE manages the repository program, a description of the key technical components of the repository program, and a summary of the DOE approach to identifying and prioritizing the remaining work required to complete an LA. Section 2 of Volume 1 summarizes the DOE understanding of the natural geologic and hydrologic systems of the Yucca Mountain site.

- Volume 2, "Preliminary Design Concept for the Repository and Waste Package," describes DOE preliminary design concepts for the repository surface facilities, underground facilities, and waste packages.

- Volume 3, "Total System Performance Assessment," describes how scientific and engineering results are used in assessments of repository performance. It presents results from computer models of the expected performance of a geologic repository at Yucca Mountain under a range of conditions and various design options over tens of thousands of years.

- Volume 4, "License Application Plan and Costs," describes the remaining work that DOE plans to perform to support the Secretary's site recommendation decision and submittal of an LA and provides an estimate of the cost of this work. This volume also describes the DOE approach to identifying and prioritizing the remaining work.

- Volume 5, "Costs to Construct and Operate the Repository," provides an estimate of the costs to construct, operate, and permanently close a repository, based on the preliminary design concepts.

## 1.2 WASTE FORMS DESTINED FOR GEOLOGIC DISPOSAL

By far the largest quantity of waste destined for geologic disposal is spent nuclear fuel from 118 commercial nuclear power reactors at 74 sites across the United States; 104 of these reactors are still in operation and generate about 20 percent of the country's electricity. Under standard contracts that DOE executed with utilities, beginning in 1983, under the Nuclear Waste Policy Act of 1982, DOE is to accept spent nuclear fuel from utilities for disposal. Until that happens, utilities must safely store their spent nuclear fuel in compliance with NRC regulations. As of December 1998, commercial spent nuclear fuel containing approximately 38,500 metric tons of heavy metal (MTHM) was stored in 33 states at 72 commercial power reactor sites and one storage site. If the existing nuclear power plants complete their 40-year license periods, they would generate approximately 87,000 MTHM of spent nuclear fuel, as shown in Table 1-1. If the existing commercial nuclear power plants were granted 10-year license extensions by NRC, they could generate approximately 105,000 MTHM of spent nuclear fuel.

Commercial (light water) reactors in the United States use uranium fuel that has been enriched generally to between 3 and 5 percent, by weight, of uranium-235, the fissionable isotope of uranium. Naturally occurring uranium ore has approximately 0.7 percent uranium-235 and 99.3 percent uranium-238. After the fuel has been irradiated in a reactor and is "spent," it contains approximately 95 percent uranium-238, 1 percent uranium-235, 1 percent plutonium, and 3 percent other elements that are products of the fission process. Thus, about 95 percent of the MTHM in commercial

Table 1-1. Approximate Inventories of Nuclear Waste Destined for Geologic Disposal and Quantities Planned for Yucca Mountain

| Categories of Nuclear Waste | Approximate Total Inventory | Planned for Yucca Mountain |
|---|---|---|
| Commercial spent nuclear fuel | 87,000[a]–105,000 MTHM[b] | 63,000 MTHM[c] |
| DOE spent nuclear fuel | 2,500 MTHM | 2,333 MTHM[d] |
| High-level radioactive waste | 10,000 MTHM equivalent | 4,667 MTHM equivalent[e,f] |

[a] Based on 40-year reactor lifetimes

[b] Based on 10-year license extensions

[c] May include 32 MTHM or more of mixed uranium/plutonium-oxide spent nuclear fuel

[d] Includes 65 MTHM of naval spent nuclear fuel

[e] Includes 640 MTHM equivalent of commercial high-level radioactive waste and 4,027 MTHM equivalent of defense high-level radioactive waste

[f] May include 18 MTHM or more of immobilized plutonium

spent nuclear fuel comes from uranium-238 that was in the original uranium ore.

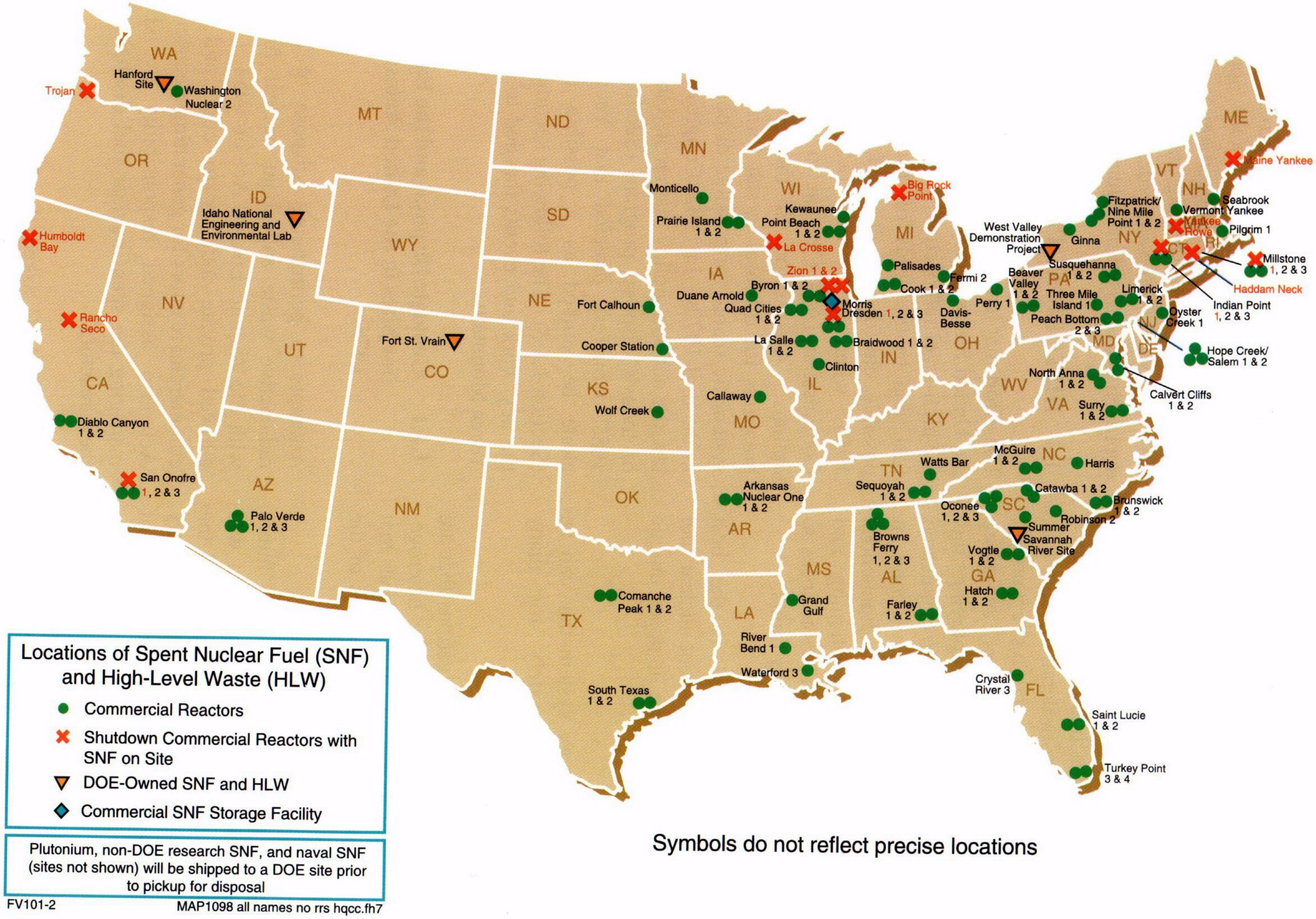
The balance of the wastes destined for disposal in a geologic repository are DOE spent nuclear fuel and high-level radioactive waste. Most of the wastes result from defense activities; others are of commercial origin but are now under DOE management. DOE spent nuclear fuel includes naval spent nuclear fuel and irradiated fuel from weapons production, domestic research reactors, and foreign research reactors. High-level radioactive waste is the chemical byproduct of reprocessing spent nuclear fuel, mostly to extract weapons-grade nuclear materials. For disposal in a geologic repository, high-level radioactive waste would be processed into a solid glass form and placed into approximately 20,000 canisters. In addition, DOE may dispose up to 50 MTHM of surplus weapons plutonium. Some could be immobilized in ceramic discs that would be embedded in high-level radioactive waste. The remainder could be formulated into a mixed uranium/plutonium-oxide fuel and used in commercial nuclear power reactors. The current planning basis is 18 MTHM of immobilized plutonium and 32 MTHM of mixed-oxide fuel, but this split is subject to change. No liquid wastes or hazardous wastes regulated under the Resource Conservation and Recovery Act of 1976 would be disposed of in a geologic repository. The approximate total inventories of DOE spent nuclear fuel and high-level radioactive waste and the quantities planned for disposal at Yucca Mountain are shown in Table 1-1.

Figure 1-2 shows 78 sites in 35 states where the nuclear materials destined for geologic disposal are currently stored.

Under the Nuclear Waste Policy Act of 1982, no more than 70,000 MTHM may be emplaced in the nation's first repository until a second repository is in operation. As a matter of policy, DOE has determined that 63,000 MTHM of commercial spent nuclear fuel, and 7,000 MTHM of DOE spent nuclear fuel and high-level radioactive waste, would be disposed of at Yucca Mountain, as shown in Table 1-1. As this table shows, the projected quantities of waste ultimately destined for geologic disposal exceed 70,000 MTHM. As explained in Volume 2, Section 7, the reference repository design is based on 70,000 MTHM, but there appears to be room for expansion.

## 1.3 TECHNICAL CHALLENGES POSED BY PERMANENT GEOLOGIC DISPOSAL

Hazards posed by spent nuclear fuel and high-level radioactive waste are initially high, but they decline dramatically with time (unlike toxic materials like lead, mercury, and arsenic that remain hazardous indefinitely). The cancer risk from ingesting radioactive materials found in spent nuclear fuel that has been removed from a reactor for 10 years is about 1,000 times greater than that from ingesting naturally occurring uranium ore. After a thousand years, the hazard difference is reduced by a factor of about 100 due to radioactive decay (Murray 1994, Figure 17). Nonetheless,




Symbols do not reflect precise locations

As of October 30, 1998

Figure 1-2. Locations of Spent Nuclear Fuel and High-Level Radioactive Waste Destined for Geologic Disposal spent nuclear fuel and high-level radioactive waste must be isolated from the human environment for many thousands of years to protect public health and safety.

There is a worldwide scientific consensus that deep geologic disposal is the best available option for disposing of high-level radioactive waste and spent nuclear fuel. The United States is pursuing this option, as are most other countries that use nuclear power and have active waste management programs. The DOE approach to disposal at Yucca Mountain deploys a defense-in-depth strategy that would rely on the natural features of a site working in concert with engineered barriers, including robust waste packages. First, deploying this strategy would contain the waste within engineered barriers for thousands of years and second, it would limit the eventual migration of radionuclides to the human environment. Containing and isolating the waste would keep radiation doses to exposed individuals below regulatory limits.

Although deep geologic disposal is the best available option for disposing of spent nuclear fuel and high-level radioactive waste, it poses unique technical challenges:

- Designing a repository system that can be expected to perform safely for many thousands of years
- Conducting scientific investigations that are carefully planned to characterize heterogeneous geologic formations in a manner that does not damage the very properties of the site that make it promising
- Answering questions about the future climate conditions, the conditions that will exist within the repository system, and the disruptive events that might affect repository system performance over many thousands of years
- Designing waste packages that must contain waste for tens of thousands of years

Uncertainty in evaluating long-term repository performance does not necessarily mean that the risks are significant; it does mean, however, that a range of outcomes is possible. A successful repository development plan must accommodate residual uncertainties and still provide reasonable assurance of safety. The DOE approach to managing the remaining uncertainties is to reduce them through further testing and to mitigate them with appropriate repository design features. This approach is discussed in Volume 4.

## 1.4 HISTORICAL PERSPECTIVE

The effort that led to the formal adoption in law of the United States policy of deep geologic disposal for high-level radioactive waste and spent nuclear fuel, and to the study of Yucca Mountain as a possible site for such disposal, began in the mid-1950s when the former U.S. Atomic Energy Commission (AEC) began to research disposal options. After efforts in the 1960s to test the prospects for disposal in salt formations, a more systematic search for possible disposal sites began in the mid-1970s. In 1982, Congress enacted into law the national policy that created the framework of today's disposal program (Section 1.4.2). In 1987, Congress directed that Yucca Mountain alone be studied as a possible disposal site (Section 1.4.3). The following sections summarize the key work and events that led to the study of Yucca Mountain.

### 1.4.1 Geologic Disposal and the Early Search for Sites in the United States: 1954–1975

Attempts to permanently dispose of high-level radioactive waste and spent nuclear fuel began with the Atomic Energy Act of 1954. This Act allowed private industry to build and operate commercial reactors for generating electricity. The Act also assigned responsibility to AEC for managing the spent nuclear fuel discharged from these reactors.

In 1955, AEC asked the National Academy of Sciences for advice on shaping sound scientific research into ways of managing and disposing of radioactive waste. Two years later, an Academy committee reported that radioactive waste can be disposed of safely underground in a variety of ways and at a large number of sites in the United States. The committee further reported that the most promising method of underground disposal at the time appeared to be in salt deposits (National Research Council, Committee on Waste Disposal 1957, pp. 3–4).

Acting on the Academy's findings, AEC commissioned the U.S. Geological Survey (USGS) to prepare a detailed report on the salt deposits in the United States. This report provided a starting basis for the subsequent search for disposal sites in salt formations. Between 1962 and 1972, AEC continued to focus on investigating salt as a potential host rock.

Technical problems encountered in a demonstration project in an abandoned salt mine in Lyons, Kansas, and intense local political opposition to developing the mine as a national geologic repository led AEC to reevaluate its strategy. AEC decided to make two fundamental changes to broaden the scientific basis for the program. First, AEC decided to greatly expand its geologic program by exploring bedded salts and salt domes in states other than Kansas and by looking at other types of potential host rocks. Second, AEC decided to evaluate disposal methods other than deep geologic burial.

The objective of the expanded geologic program was to identify sites where pilot repositories could be constructed for demonstrations of performance. In addition to investigating bedded salt deposits and salt domes, background data on the abundant and widespread deposits of shale, mudstone, and claystone were collected.

An evaluation of alternative disposal methods, begun in 1972, considered different concepts for geologic disposal on land, disposal in the ocean bed and in polar ice sheets, ejection into outer space, and transmutation of radioactive elements. When the evaluation was completed in 1974, disposal in a geologic repository remained the preferred alternative.

Through the Energy Reorganization Act of 1974, Congress dissolved AEC and established two agencies, NRC and the U.S. Energy Research and Development Administration (ERDA). ERDA carried on the program begun by AEC for siting and developing geologic repositories. NRC was established as an independent regulatory agency and given the responsibility for licensing any geologic repositories that might be developed.

### 1.4.2 Development of a National Policy and a Broader Search for Disposal Sites: 1976–1982

In 1976, ERDA expanded the geologic disposal evaluation program to study different host rocks for repository sites and received authorization to greatly increase funding for the program. Known as the National Waste Terminal Storage Program, this project was the direct predecessor of today's geologic repository program.

The objective of the National Waste Terminal Storage Program was to site and develop six geologic repositories. The strategy was to site the first two repositories in salt and start pilot operations in 1985. The other four repositories were to be built in other host rocks such as shale, basalt, or crystalline rock and were expected to start receiving waste in the mid-1990s.

The number of repositories proposed depended on two factors. One was the optimistic forecast, at that time, for the future growth of commercial nuclear power in the United States; the other was the belief that developing multiple repositories would distribute the burden of waste disposal among several states and regions. Consistent with this approach, ERDA decided to start investigations in 36 states. However, reaction by the governors of these states when notified of ERDA intentions, together with other factors, led ERDA to scale back its plans and concentrate mainly on salt sites.

At about the same time as the start of the systematic screening program for salt sites, ERDA started a search for potential repository sites on federal land, especially land where radioactive materials were already present. The Comptroller General of the United States and the U.S. House of Representatives later recommended this approach. ERDA soon narrowed its search to the Hanford Reservation in the State of Washington and the Nevada Test Site in southern Nevada. Within these large sites, ERDA focused its search on smaller land units after evaluating geologic and hydrologic suitability for a repository.

In October 1977, ERDA became DOE, which was elevated to a cabinet-level department within the Executive Branch. Shortly thereafter, DOE formed an internal task force to make recommendations leading to formulating an administration policy. Among other things, the internal task force reported the following (draft report of Task Force for Review of Nuclear Waste Management, DOE Directorate of Energy Research, February 1978):

- A majority of independent technical experts had concluded that safe disposal in geologic repositories was feasible.

- Reprocessing was not required for safe disposal.

- The National Environmental Policy Act process should be an essential part of the waste management program.

- Responsibility for waste management policy should be raised to a higher level in DOE.

In March 1978, President Jimmy Carter established another task force, composed of representatives of DOE, NRC, and 12 other federal agencies that came to be known as the Interagency Review Group on Nuclear Waste Management. Its purpose was to formulate recommendations for a national policy for the long-term management of radioactive waste. The group obtained a broad range of views from many sources including state and local governments, Indian tribes, environmental organizations, and the nuclear industry. The group's most important recommendations can be summarized as follows (Interagency Review Group on Nuclear Waste Management 1979):

- Research and siting programs should be designed to provide candidate repository sites in a variety of host rocks with different geologic characteristics.

- The country should have at least two repositories operating before the end of the century in different regions, recognizing that safety and technical considerations must remain the principal bases for site selection.

- The development and operation of a repository should proceed in a technically conservative, step-by-step manner, and permit waste retrievability for some period of time.

In February 1980, President Carter announced a comprehensive program for managing radioactive waste. The principal points addressed by the plan included the following for geologic disposal:

- Providing an effective role for state and local governments in the disposal program

- Adopting an interim planning strategy, based on geologic disposal, pending completion of the EIS on alternative disposal methods

In October 1980, following public review and comment, DOE issued an EIS that evaluated the various disposal methods under consideration (DOE 1980). On May 14, 1981, DOE selected mined geologic repositories as the preferred means for the disposal of spent nuclear fuel and high-level radioactive waste (46 FR 26677).

#### 1.4.2.1 Early Studies Leading to Yucca Mountain

As early as 1977, the Nevada Test Site was considered as a possible repository site. In 1976, USGS pointed out that the region offered a variety of geologic media. Scientists who had been studying the region since the late 1950s had developed "a wealth of hydrological, geological, and geophysical data and information which, in many respects, is unequaled anywhere else in the United States" (letter from Dr. Vincent McKelvey, USGS Director, to Richard W. Roberts, ERDA

Assistant Administrator for Nuclear Energy, July 9, 1976). The USGS cited a number of reasons for considering the test site:

- Southern Nevada is characterized by closed hydrologic basins. This means that groundwater does not discharge into rivers that flow to major bodies of surface water.

- Long flow paths occur between potential repository locations and groundwater discharge points.

- Many of the rocks found at the Nevada Test Site have geochemical characteristics that are favorable for waste isolation.

- The Nevada Test Site is located in an arid region. With the very low rate of groundwater recharge, the amount of moving groundwater is also low especially in the unsaturated rock above the water table.

As described in the DOE environmental assessment of the Yucca Mountain site (DOE 1986a, pp. 2-14–2-15), the search of the Nevada Test Site was eventually limited to the southwestern portion of the site and nearby government owned and controlled land where no weapons testing had been or would be conducted. One of the more promising rock types in the area is tuff, a rock composed of volcanic ash. DOE asked the National Academy of Sciences for its views on tuff as a possible host rock for a repository and received a favorable response. At about the same time, USGS recommended that attention be focused on Yucca Mountain. In 1978, the first exploratory hole drilled at Yucca Mountain confirmed the presence of thick units of tuff.

#### 1.4.2.2 Studying the Unsaturated Zone

In the 1970s, a USGS scientist, Dr. Isaac J. Winograd, advanced the concept of disposing of waste in the thick, unsaturated zones of the semiarid regions of the southwestern United States. In February 1982, USGS sent a letter to DOE pointing out that there were considerable advantages that might be offered by the unsaturated zone at Yucca Mountain (letter from John B. Robertson, Chief, Office of Hazardous Waste Hydrology; Gary Dixon, Acting USGS Program Coordinator, Nevada Nuclear Waste Site Investigation Program; and William E. Wilson, Chief, Nuclear Hydrology Program to Mitchell Kunich, DOE Nevada Operations Office, February 5, 1982). According to the letter, the strategy of unsaturated zone disposal at Yucca Mountain "rests on the argument that the amount of water reaching the repository will be very small" and that a repository can be designed that will allow such water to pass through the repository into the permeable rocks below with minimal contact with the canisters of waste.

Disposing of waste in the unsaturated zone also offers the possibility of far easier access for monitoring during the operational period of a repository and for waste retrieval, should that become necessary.

### 1.4.3 Establishing National Policy: The Nuclear Waste Policy Act of 1982

In 1982, the 97th Congress passed the Nuclear Waste Policy Act of 1982, which for the first time established in law a comprehensive national policy for the management and final disposal of spent nuclear fuel and high-level radioactive waste. Among other things, the Act specified a process and schedule for siting two repositories. The U.S. Environmental Protection Agency (EPA) was charged with issuing generally applicable standards for limits on releases of radioactive materials from repositories to the environment. NRC was directed to develop the requirements and criteria that it would apply in authorizing construction, operation, and closure of a geologic repository. The Act directed DOE to issue general guidelines for recommending sites for repositories. The Act established within DOE the Office of Civilian Radioactive Waste Management (OCRWM). The OCRWM director, who conducts the program, reports directly to the Secretary of Energy.

Shortly after the Act was passed, DOE identified nine sites that were then under consideration for the first repository. This identification was consistent with congressional direction. These nine sites included the following:

- Four sites in bedded salt (Deaf Smith County and Swisher County in the Texas panhandle and Davis Canyon and Lavender Canyon in Utah)
- Three salt domes (Richton and Cypress Creek in Mississippi and Vacherie in Louisiana)
- A site in tuff (Yucca Mountain in Nevada)
- A site in basalt (Hanford in Washington)

In December 1984, following the required concurrence by NRC, DOE issued the siting guidelines that were prescribed in the Act. The guidelines (10 CFR 960) contained provisions that required evaluating repository system performance against the standards that were to be established by EPA and the performance objectives established by NRC in its 1983 rule governing the licensing of geologic repositories (10 CFR 60).

The Act envisioned that DOE would use its siting guidelines to screen, identify, and nominate multiple sites in different geologic media as suitable for characterization. A subset of these sites was then to be recommended to and approved by the President for characterization to determine suitability for development as a repository. In support of this process, DOE was to issue an environmental assessment for each site that was nominated. Each environmental assessment was required to present an evaluation of the site according to the guidelines. This assessment also was to evaluate the impact on public health and safety and on the environment as a result of characterization and repository development.

In December 1984, DOE issued for public comment the draft environmental assessments for the nine potentially acceptable sites for the first repository. After accommodating comments, especially a recommendation by the National Academy of Sciences to develop and use an improved decision-aiding method for site selection, in May 1986 DOE issued final environmental assessments for the Yucca Mountain site and four other nominated sites. Also in May 1986, DOE submitted to the President its recommendation of three sites to be characterized for selection of the first repository site (DOE 1986b), and the President approved the recommendation on May 28, 1986. The three sites approved for characterization were the Deaf Smith County site in Texas (salt), the Hanford site in Washington (basalt), and the Yucca Mountain site in Nevada (tuff).

While DOE was developing its assessments of the potentially acceptable sites for the first repository, DOE also began the Nuclear Waste Policy Act process of identifying sites for a second repository. The DOE search for these sites centered on granite formations in 17 eastern, southern, and midwestern states. In February 1986, DOE issued draft area recommendation reports and held hearings on these reports in all 17 states. In May 1986, the Secretary of Energy decided to indefinitely defer all work to seek a second site. As stated in the *Mission Plan Amendment for the Office of Civilian Radioactive Waste Management* (DOE 1987), this decision was made for the following reasons:

- Progress in siting the first repository and confidence in the suitability of the three sites approved by the President for site characterization
- Generally declining forecasts of the quantities and rates at which spent nuclear fuel would be discharged from reactors
- Later estimates of the time when the second repository would be needed
- Prudent fiscal management and responsibility
- The expectation of receiving congressional approval for developing a monitored retrievable storage facility

Once the President approved the three sites for characterization in 1986, preparation for characterization began. It soon became clear that more time would be needed to prepare for site characterization and to develop the plans required by the Act. In addition, it became apparent that more time than previously planned would be needed to obtain the environmental permits and other approvals necessary to gain access to the sites selected for characterization. These factors prompted DOE to announce a 5-year delay in the repository schedule with waste acceptance for geologic disposal to start in 2003 (DOE 1987).

### 1.4.4 The Nuclear Waste Policy Amendments Act of 1987

Faced with the delay in the repository schedule, the escalating estimates of costs for characterizing three sites, and growing public concerns about the siting of geologic repositories, the 100th Congress devoted considerable attention to the waste management program. On December 21, 1987, Congress approved legislation amending the Nuclear Waste Policy Act of 1982. Known as the Nuclear Waste Policy Amendments Act of 1987, this legislation was signed into law by President Ronald W. Reagan on December 22, 1987.

The Amendments Act substantially revised the federal policy established in 1982 for development of geologic repositories. It directed that only Yucca Mountain be characterized to evaluate its suitability for development as a geologic repository. The Amendments Act also prohibited site-specific work directed toward siting a second repository and nullified the DOE proposal to locate a monitored retrievable storage facility at a site at the Clinch River in Oak Ridge, Tennessee.

### 1.4.5 The Site Characterization Program

The Nuclear Waste Policy Act of 1982 requires that a general plan be prepared for characterizing a candidate repository site. Each site characterization plan must be submitted for review and comment to NRC. It must also be submitted to either the state in which a repository is proposed to be located or to the governing body of any Indian tribe on whose reservation the repository is proposed to be located.

In 1988, DOE produced the site characterization plan called for in the Act (DOE 1988c). This plan described a comprehensive program to provide the information needed to evaluate the suitability of the Yucca Mountain site against criteria in DOE siting guidelines and to satisfy NRC requirements for licensing. Implementation of this plan was intended to provide the information needed to design a repository that would work in concert with the site and to evaluate the performance of the repository and site as a system. DOE released the plan in draft form for review by NRC, the State of Nevada, and other interested parties. After considering the comments received, DOE issued the final plan in December 1988.

In 1989, after enactment of the Amendments Act and issuance of the site characterization plan, the Secretary of Energy reassessed DOE plans and schedules for repository development. Consequently, the Secretary of Energy directed the program to focus on scientific investigations without pressures from unrealistic schedules. Implementation of the Secretary of Energy's direction required extending the schedule for the start of repository operations from 2003 to 2010.

The site characterization program included surface-based testing and investigations, underground testing as required by NRC regulations, and laboratory studies and modeling activities for evaluation of repository performance. The single largest effort of the planned site characterization program was constructing the Exploratory Studies Facility to gain access to the subsurface for exploration and testing at the depth of the proposed repository. Work began on construction of this facility in late 1992 and excavation with a tunnel boring machine began in September 1994. The 4.9-mile-long underground tunnel that comprises the main part of the Exploratory Studies Facility was completed in April 1997. Testing of this facility has led to substantially increased knowledge and understanding of the rock properties and hydrologic characteristics of the geologic formation in which the repository would be constructed. Future work in the Exploratory Studies Facility will focus primarily on thermal and hydrologic testing and confirmation of the rock properties.

### 1.4.6 The Energy Policy Act of 1992

Title VIII of the Energy Policy Act of 1992 revised the regulatory framework for geologic disposal at Yucca Mountain. This legislation nullified, for application at the Yucca Mountain site, the general environmental standards promulgated by EPA under the Nuclear Waste Policy Act of 1982. These standards had established limits for the amount of each radionuclide in spent nuclear fuel and high-level radioactive waste that could be released to the environment. For application to Yucca Mountain, the Energy Policy Act of 1992 directed EPA to establish a limit on annual radiation doses to individual members of the public. Further, the Energy Policy Act of 1992 stipulated that the new EPA site-specific standards be based on, and consistent with, findings and recommendations of the National Academy of Sciences regarding development of such standards. NRC was directed to conform its regulations as necessary to be consistent with revised EPA standards.

On August 1, 1995, the Committee on Technical Bases for Yucca Mountain Standards, of the Academy's National Research Council, issued its report *Technical Bases for Yucca Mountain Standards* (National Research Council 1995). EPA is currently engaged in a rulemaking process to establish standards for a repository at the Yucca Mountain site. NRC is considering how to revise its licensing criteria for geologic repositories to implement EPA standards, when issued, and to be consistent with the Academy's recommendations (NRC 1997b).

The Energy Policy Act of 1992 also created a requirement for postclosure oversight of Yucca Mountain if the site is developed as a geologic repository. Following repository closure, the Secretary of Energy must continue to oversee the site to prevent any activity at the site that poses an unreasonable risk of breaching the repository's engineered or geologic barriers or of increasing the exposure of individual members of the public to radiation beyond allowable limits.

### 1.4.7 Program Redirection and the Viability Assessment

At the direction of the Secretary of Energy, DOE conducted extensive internal and external reviews of the program during 1994. As a result of these reviews, DOE identified cost-cutting measures that reduced by approximately $1 billion the projected cost to complete site characterization and submit an LA to NRC. The revised DOE plans were documented in the 1994 *Civilian Radioactive Waste Management Program Plan* (DOE 1994) and were endorsed by Congress as a basis for increased funding for fiscal year 1995. However, the fiscal year 1996 appropriation to the program did not support the continuation of the approach outlined in the 1994 program plan. In response to the 1996 appropriation and the outlook for future funding, DOE prepared a new program plan (DOE 1996) that retains the objective of submitting an LA within a reasonable time, but that requires only moderately increased funding in future years.

The revised program strategy is designed to maintain the momentum that has been achieved in the scientific investigation of the Yucca Mountain site and to regain target dates for determining the site's suitability for a geologic repository and for submitting an LA. Part of the revised program strategy was to redirect project efforts to address the major unresolved technical questions and to complete an assessment of the viability of licensing and constructing a repository at the Yucca Mountain site. In the 1996 program plan, DOE stated its intention to complete the VA by 1998. In the 1997 Energy and Water Development Appropriations Act, Congress directed DOE to provide the VA to the President and to the Congress.

The VA is a DOE management tool as well as a report to the President and the Congress on progress and prospects. The VA describes the strategies that DOE has developed to deal with uncertainties associated with estimates of long-term repository performance and to ensure that public health and safety will be protected before and after the repository is permanently closed (Section 1.8, and Volume 4, Section 2). DOE has used these strategies to guide identification and prioritization of the remaining work required to recommend the site and, if the site is recommended and the recommendation is accepted, to complete an LA (Volume 4, Section 3). The results of the VA also will be useful in developing the EIS that must accompany the site recommendation and LA.

## 1.5 UPDATING THE REGULATORY FRAMEWORK

The Nuclear Waste Policy Amendments Act of 1987 and the Energy Policy Act of 1992 changed the statutory requirements that apply to the siting and licensing of a geologic repository at Yucca Mountain. DOE, EPA, and NRC are engaged in activities to update their respective implementing regulations. The following sections briefly describe the status of these updates.

### 1.5.1 U.S. Department of Energy Siting Guidelines

One of the key elements of the DOE revised program plan (DOE 1996) was to update the regulatory framework for a repository at Yucca Mountain. In December 1996, DOE published a Notice of Proposed Rulemaking (61 FR 66158) on its siting guidelines in 10 CFR 960 and proposed to add a new, site-specific Subpart E for evaluation of the suitability of the Yucca Mountain site for development as a repository. The proposed revisions take into consideration the changes in law and national policy regarding geologic disposal since the guidelines were issued in 1984, and the results of DOE site characterization activities. The proposed Subpart E would not require an evaluation of how individual subsystems of the repository must perform. Rather, it would assess how the total repository system would perform and compare that performance to the limits on the radiation doses that could be received by members of the public living near Yucca Mountain. DOE has concluded a lengthy public comment period on the proposed rule but has not published a final rule. The regulatory limit on doses will be established by EPA, as discussed next.

### 1.5.2 U.S. Environmental Protection Agency Public Health and Safety Standards

As described in Section 1.4.6, the Energy Policy Act of 1992 directed EPA to issue new public health and safety standards that will establish limits on annual radiation doses to individual members of the public; these standards are to be based on and consistent with findings and recommendations of the National Academy of Sciences. EPA contracted with the Academy for these findings and recommendations, and the Academy issued its report in 1995 (National Research Council 1995). EPA is expected to publish a proposed rule for site-specific health and safety standards in a new regulation.

### 1.5.3 Nuclear Regulatory Commission Requirements and Criteria

The Nuclear Waste Policy Act of 1982 directed NRC to establish technical requirements and criteria for the approval or disapproval of applications to construct repositories, licenses to receive and possess spent nuclear fuel and high-level radioactive waste, and authorizations to permanently close repositories. Under the Energy Policy Act of 1992, NRC will modify its current requirements and criteria, as necessary, to be consistent with EPA Yucca Mountain-specific standards when issued. NRC has approved development of a new regulation, 10 CFR 63, to contain site-specific requirements for a possible Yucca Mountain repository (NRC 1998). Until NRC issues 10 CFR 63, DOE will comply with existing requirements in 10 CFR 60.

## 1.6 HOW THE U.S. DEPARTMENT OF ENERGY MANAGES THE REPOSITORY PROGRAM

DOE work at Yucca Mountain is directed by OCRWM, an office within DOE that was created by the Nuclear Waste Policy Act of 1982. Headquartered in Washington, D.C., OCRWM implements the federal policy for permanent disposal of high-level radioactive waste and spent nuclear fuel. OCRWM has delegated to the Yucca Mountain Site Characterization Office the authority, responsibility, and accountability for technical and quality performance, cost, and schedule of the Yucca Mountain Site Characterization Project (YMP). The Yucca Mountain Site Characterization Office directs and manages the YMP to accomplish successfully the project's goals and objectives in compliance with the program objectives established by OCRWM.

### 1.6.1 Project Management

Carrying out the repository program involves conducting and integrating a wide variety of scientific and engineering work. Since its inception in 1982, OCRWM has employed a number of contractors with specific technical and management expertise to assist in this endeavor. Figure 1-3 shows the organizations assisting OCRWM in conducting the repository program.

A management and technical support services contractor provides specialized expertise in establishing and monitoring overall program requirements, reviewing and analyzing requirements for implementing plans and baselines, supporting policy analyses and planning activities, and preparing and maintaining program technical guidance and program management plans.

The management and technical support services contractor also assists OCRWM in the technical oversight of program activities by conducting independent assessments of contractor compliance with statutory requirements and best business practices in areas such as environmental, safety, and health, and proposed construction methodologies. The management and technical services contractor also provides technical support for reviewing design analyses, design basis documents, materials and waste form testing, and process models. Further, the contractor provides specialized scientific support for independently evaluating the accuracy and appropriateness of scientific tests, data, and models being developed for the program.

The majority of the technical work and product development is performed by the Civilian Radioactive Waste Management System management and operating contractor (CRWMS M&O). TRW Environmental Safety Systems Inc. is the prime contractor. Teamed with TRW, with unique technical expertise in science and engineering, are 13 other private firms, 7 DOE national laboratories, and USGS. Together, this team performs the site characterization studies, engineering design, and performance assessment work that forms the core of the VA and that will be the basis for future decisions on site recommendation and the LA. The M&O also provides training, security, and procurement; oversees facilities management and motor pool operations, records management and technical document control; and conducts public information and outreach programs.

As described in Section 1.4.2.1, USGS has been directly involved in the study of Yucca Mountain since the late 1970s. USGS operates independently of the CRWMS M&O but receives technical direction and integration support through the CRWMS M&O organization.

OCRWM employs other contractors for specialized tasks. The quality assurance technical support contractor helps OCRWM manage the quality assurance program; comply with NRC requirements; conduct audits, surveillances, and onsite inspections; and maintain quality assurance documents. The communications network and computer systems support services contractor provides information technology and telecommunications. Office services are provided by the administrative support services contractor. The repository environmental impact statement contractor is writing the EIS using technical information developed by M&O scientists and engineers.

OCRWM also has a cooperative agreement with the Nevada university system for technical investigations. OCRWM purchases site facility services, such as security, from the Nevada Test Site management and operating contractor through a memorandum of understanding with the DOE Nevada Operations Office.

OCRWM reviews all contractor deliverables before acceptance and implements processes for

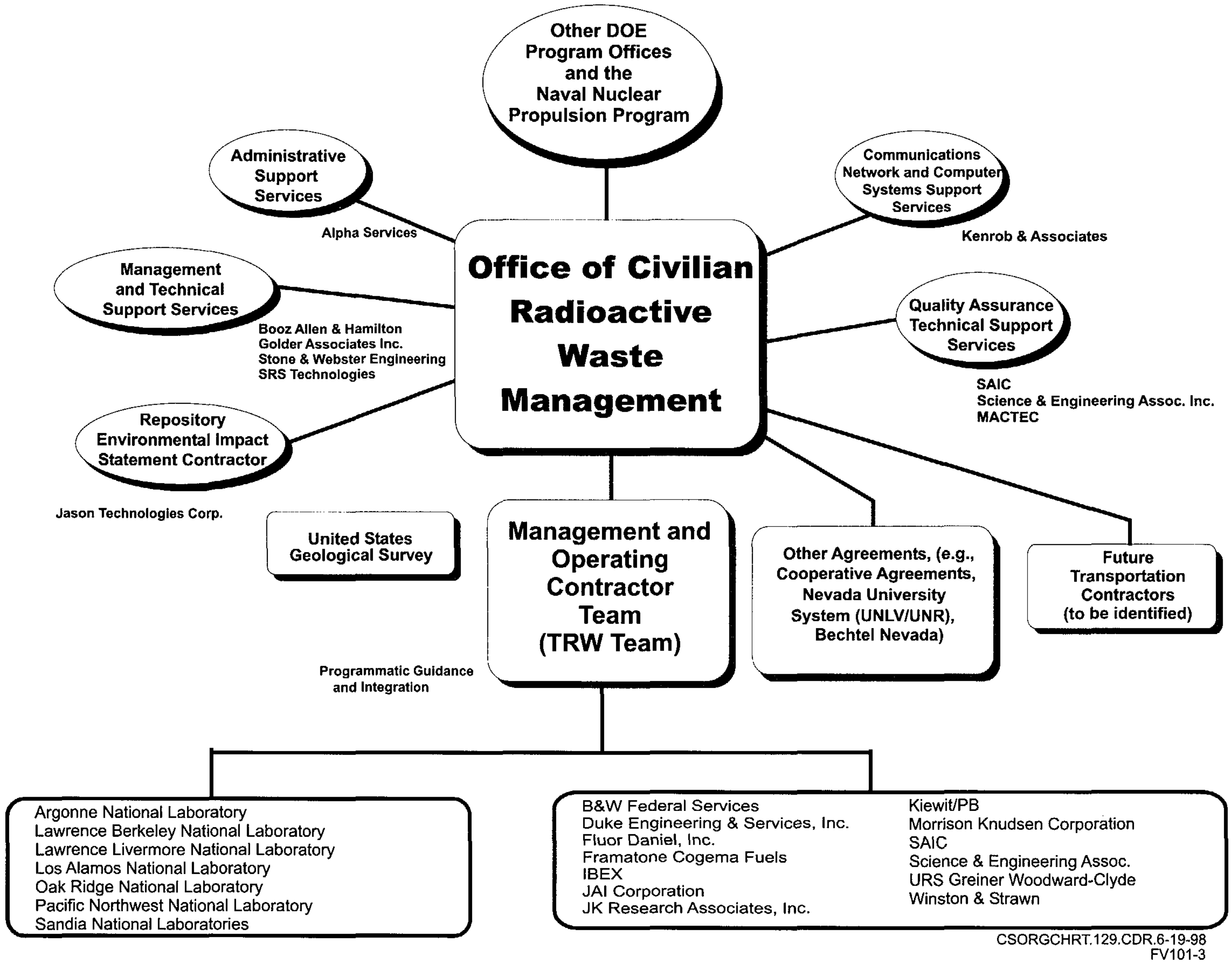



Figure 1-3. Office of Civilian Radioactive Waste Management Contractor Organization

planning, scheduling, budgeting, and performance measurement of all repository program activities.

In the future, if the site is approved for repository development, OCRWM may hire additional contractors with expertise in transportation of nuclear waste.

### 1.6.2 Systems Engineering

In a geologic repository, multiple engineered barriers (collectively, the engineered barrier system) and natural geologic barriers must work in concert to contain and isolate waste for many thousands of years. The integration of natural and engineered barrier systems is facilitated through a systems engineering approach.

In systems engineering, all requirements for the system being designed are first identified. In the case of a geologic repository, the engineered components of the repository system must be designed to work together with the preexisting natural system to meet the overall system requirements. Next, the system requirements are translated into design criteria for the waste packages and other engineered components of the repository. Particular attention is paid to evaluating how the components of the repository work together so that the ultimate configuration of components enhances overall system performance. As the design progresses from the conceptual through the preliminary stages, and on to the design to be included in the LA, the design is reviewed to ensure that it continues to meet all regulatory requirements and is properly integrated. This activity is referred to as requirements and design verification. Changes to the design and specifications are documented and controlled in accordance with the approved quality assurance program.

Development of the repository design is part of an iterative process of testing, design, and performance assessment. As new information about the natural systems has become available through the scientific investigations, analysts have reevaluated the expected performance of the repository and waste package designs, and, as appropriate, the engineers have modified the designs. This iteration of testing, design, and performance assessment is discussed further in Section 1.7.3.

### 1.6.3 Quality Assurance of Information and Materials

The DOE quality assurance program serves to ensure the quality of data, analyses, and materials that are related to quality-affecting structures, systems, or components; that is, those structures, systems, or components that are important to radiological safety or waste isolation. The quality assurance program satisfies NRC requirements and has been approved by NRC. This program requires that all quality-affecting work be performed according to written and approved procedures. It prescribes requirements for documentation of quality-affecting work and employs audits and surveillances to ensure the quality of such work.

The Office of Quality Assurance is headquartered in Las Vegas, Nevada, to facilitate oversight of quality-affecting tasks in the day-to-day work of site characterization. However, the director of the Office of Quality Assurance reports directly to the OCRWM director in Washington, D.C. To further increase the organizational independence of quality assurance personnel and provide for greater consistency in interpretation and application of requirements across the program, the quality assurance organizations formerly maintained by the CRWMS M&O and USGS have been consolidated into a single organizational unit reporting to the director of the Office of Quality Assurance.

The quality assurance program applies to data collection in the field, laboratory testing, model development, and design processes. It requires documentation that individuals are educated, experienced, and qualified to perform assigned work; it also requires that they be trained in applicable procedures. The quality assurance program requires documentation of this work so that an independent reviewer can trace how, where, and when the work was performed.

The quality assurance program applies to all organizations that do quality-affecting work, including DOE, contractors, and vendors who supply goods and services. All quality-affecting work is subject to audits and surveillances by the Office of Quality Assurance. The objective of the audits and surveillances is to verify that all quality assurance requirements are being met, to allow early identification and correction of problems, and to provide information that managers can use to improve management processes.

### 1.6.4 Quality Assurance and the Viability Assessment

DOE considered project-generated and outside information in developing the VA to ensure that a broad range of pertinent information and scientific interpretations was considered. Some of these data are qualified, that is, obtained or validated under the NRC-approved quality assurance program that DOE has had in place since 1990, and some are not fully qualified. There is no requirement under the OCRWM quality assurance program that all information used in the VA be qualified. However, all data directly relied on to demonstrate radiological safety or waste containment in an LA must be qualified. DOE is preparing plans for LA data qualification consistent with quality assurance program requirements. Additional nonqualified data or information may be used to corroborate the conclusions in the LA.

### 1.6.5 Controlling Samples from Field Studies

Tests on rock, water, and gas collected during site characterization are the foundation of the conceptual and computer models DOE uses to assess the expected performance of a monitored geologic repository at Yucca Mountain. The results of testing geologic samples are also a fundamental input to the design of the repository and waste packages. Therefore, DOE carefully documents and controls these samples.

Samples taken from boreholes, rock outcrops, trenches, and the underground Exploratory Studies Facility are stored in the onsite Sample Management Facility. This facility houses over 75,000 feet of rock core samples from boreholes. Approximately 18,000 noncore samples of bulk rock, soil, water, gas, and other materials are also stored in the facility. Special storage (e.g., temperature-controlled, hermetically sealed storage) is provided for certain kinds of materials to meet scientific and quality assurance requirements.

DOE maintains chain-of-custody documentation for geologic samples. This documentation includes information on where, when, and under what conditions samples were obtained; where, how, and under what conditions they have been stored; who has had custody of samples if they have been checked out; and the tests that have been conducted on samples, and by whom.

Because geologic samples are a valuable resource, a sample overview committee composed of representatives of each major project organization, including the participating national laboratories, approves the release of sample specimens for analysis by project scientists. To date, more than 28,000 specimens have been created for analysis.

### 1.6.6 Independent Regulation, Oversight, and Review, and Scientific Collaboration

To enhance public confidence, Congress provided for independent regulation and oversight of the DOE effort to site and construct a geologic repository for the nation's high-level radioactive waste. The Nuclear Waste Policy Act of 1982 gave licensing authority to NRC and provided for the participation of affected parties in the siting process. The 1987 Nuclear Waste Policy Amendments Act provided additional oversight through the creation of the Nuclear Waste Technical Review Board, which reports its findings, conclusions, and recommendations to Congress and the Secretary of Energy.

Independent peer review is an important part of the DOE quality assurance program. The quality assurance program requires documents that specify technical and quality requirements, design output documents, design analyses, procurement documents, procedures, technical reports, and data to be reviewed internally by qualified personnel who did not perform the work being reviewed. In addition, project scientists publish papers reporting their findings in peer-reviewed scientific journals and present their findings at conferences and meetings of professional societies and industry organizations. On occasion, the National Academy of Sciences provides independent reviews for issues of concern.

DOE also collaborates formally with other countries and international organizations to exchange information and develop consensus on common issues related to geologic disposal. Canada, Sweden, Switzerland, France, Japan, and Spain are bilateral partners with DOE. DOE also participates in the activities of the International Atomic Energy Agency and the Nuclear Energy Agency, which represent about 30 countries. The focus of these interactions is interpretation of site characterization data and assessment of the likely performance of a monitored geologic repository.

Interest in the Yucca Mountain project runs high among other nations that are developing their own nuclear waste management programs, and representatives from these nations frequently visit the Yucca Mountain site and meet with project scientists to learn about their work and exchange information.

### 1.6.7 Interactions with the Nuclear Regulatory Commission

If DOE submits an application to NRC for authorization to construct a monitored geologic repository at Yucca Mountain, the ensuing licensing proceeding will entail large volumes of information. Much of this information will be highly technical, including analyses of issues without precedent in a licensing proceeding. Continuing interactions with NRC—both formal briefings and informal interactions at the staff level—help develop shared expectations about licensing.

NRC has identified 10 key technical issues it considers to be most important to the performance of the proposed repository at Yucca Mountain (NRC 1997a). Nine of these issues address features and processes that are relevant to the long-term, or postclosure, performance of the repository. A tenth issue concerns the new performance standard for Yucca Mountain to be issued by EPA (Section 1.5.2). Work has been planned to address these key technical issues. Linkages between the issues and work already conducted are noted in the descriptions of the site (Volume 1, Section 2), VA reference design (Volume 2), and total system performance assessment (TSPA) (Volume 3). Volume 4, Section 4.3.3, summarizes the resolution status of each key technical issue, provides a table that shows where each issue is addressed in the VA document, and describes the protocol and process for addressing the key technical issues before submittal of the LA.

## 1.7 TECHNICAL COMPONENTS OF THE REPOSITORY PROGRAM

This section describes the three key technical components of site characterization—testing, design, and TSPA—and some concepts important to understanding them, particularly TSPA. It describes how DOE iterates testing, design, and TSPA to reduce uncertainties in assessments of repository performance, to advance the repository and waste package designs, and to identify and prioritize testing needs.

### 1.7.1 Components and Concepts of Site Characterization

Site characterization is designed to yield information to support a determination of whether or not there is reasonable assurance that a monitored geologic repository constructed at Yucca Mountain would not pose an unreasonable risk to public health and safety. As noted in the previous section, the three main components of site characterization are testing, design, and performance assessment. These three components comprise:

- Investigation of natural features and processes, through field testing conducted above and below ground and laboratory tests of rock and water samples

- Design of a repository and waste packages tailored to the site features, supported by laboratory testing of candidate materials for waste packages and design-related testing in the underground tunnels where waste would be emplaced

- Quantitative estimates of the performance of the total repository system, over a range of possible conditions and for different repository configurations, by means of computer modeling techniques that are based onsite and materials testing data and accepted principles of physics and chemistry

Some key concepts involved in site characterization follow:

- *Biosphere* is the portion of the environment inhabited by living organisms. Aspects of the biosphere that are of interest in estimating doses include the location of water wells, how much well water people drink, how much well water people use to irrigate crops, the types of crops grown, and how people and animals consume the crops.

- *Dose* is a measure of radiation exposure received by an individual. The objective of repository siting and design is to keep radiation doses to persons who may be near the repository to levels below regulatory standards.

- *Engineered barriers* are man-made features that work in conjunction with natural barriers to contain waste and isolate it from the biosphere. Engineered barriers include the waste packages into which waste forms would be placed, and the waste forms themselves. An example of a waste form is the glass form of vitrified high-level radioactive waste. The glass, in which the radionuclides are encapsulated, is a barrier to waste migration as are the container in which the vitrified waste is poured and the waste package in which the canister is placed.

- *Natural barriers* are natural features of the site that would help contain and isolate the waste and retard the migration of radionuclides to the biosphere. One example of a natural barrier at Yucca Mountain is the approximately 1,000 ft of volcanic tuff between the water table and the geologic formation in which waste would be emplaced.

- *Performance assessment* is the use of computer models of natural processes to evaluate the potential performance of both natural and man-made components of the repository. The process models are based on data from field investigations and laboratory studies and on accepted principles of physics and chemistry. In a TSPA, analysts link the results of individual process models to construct a computer model of aspects of the repository system and the biosphere that are important to the assessment of overall performance. The TSPA model is used to estimate releases of radionuclides from a repository under a range of conditions over thousands of years and the consequent possible doses to persons.

- *Radionuclides* are radioactive elements. Spent nuclear fuel and high-level radioactive waste contain a number of different radionuclides with decay times ranging from a few years to millions of years.

- *Repository system* means the engineered barriers and those natural features of the site that together act to contain waste and isolate it from the biosphere.

### 1.7.2 Total System Performance Assessment

The basis of TSPA is data from field investigations and laboratory studies, interpretations of data by recognized experts, relevant information from other documented sources, and information about design attributes of the engineered barriers. This information is used to develop models of the biosphere and of local and regional natural processes that might affect the performance of natural and engineered barriers. These process models are used to enhance understanding of important geologic processes, such as water movement in the unsaturated zone, and to provide estimates of parameter values, such as the rate at which downwardly percolating water enters the rock at the depth at which waste would be emplaced (the repository horizon). The results of such process models are then input to other models, such as models of waste package corrosion, to estimate the rate at which radionuclides could be released under the range of possible site conditions. Models of the biosphere are used to evaluate processes by which radionuclides in groundwater could come into contact with humans. Analysts then synthesize the information gained from field and laboratory studies and from process models to create conceptual models of the total repository system. These conceptual models are represented as mathematical equations and algorithms within a computer program that can be used to assess the long-term performance of the repository system.

To be meaningful, the assessment must capture all important components of the engineered and natural barriers and the processes that could affect their performance. This entails a characterization of how relevant geologic, climatic, hydrologic, geochemical, and geomechanical processes behave over time. The assessment also must capture uncertainties in understanding of the relevant processes and uncertainties in characteristics of the site and properties of man-made components of the repository. Typically, these uncertainties are expressed by specifying the relative likelihood that model parameters have a value within a range of possible values.

### 1.7.3 Iteration of Testing, Design, and Total System Performance Assessment

An important function of TSPA is to evaluate the significance of uncertainties in properties and processes by evaluating the sensitivity of calculated doses to different assumptions regarding these properties and processes. DOE uses the results of such sensitivity studies to identify and prioritize needed site characterization work, investigation of materials properties, or other design-related investigations. DOE also uses TSPA sensitivity studies to evaluate repository and waste package design options. This process proceeds iteratively: new data and design changes are incorporated into updated TSPA models, and updated TSPA sensitivity studies suggest where new data and design enhancements might be valuable. Over time, this iterative process reduces uncertainty in the performance of the repository design.

As illustrated in Figure 1-4, the testing, design, and TSPA results that are presented in this VA reflect the next-to-last cycle of iteration in the DOE characterization of the Yucca Mountain site. The first cycle began with information obtained from studies of the Nevada Test Site and the idea to dispose of high-level radioactive waste in the unsaturated zone, as described in Section 1.4.2. This cycle produced the first conceptual design for a geologic repository at Yucca Mountain (Sandia National Laboratories 1984), the DOE site characterization plan (DOE 1988c), and numerous, detailed study plans to implement the overall site characterization plan. Continuing the site characterization process, DOE began to build performance assessment models and conducted benchmark performance assessments of the total repository system in 1991, 1993, and 1995 (Barnard et al. 1992; Wilson et al. 1994; CRWMS M&O 1994a; CRWMS M&O 1995). Between these benchmark assessments, DOE conducted many performance assessments to evaluate selected features of the site and the evolving design. DOE used these total system and subsystem performance assessments to evaluate design options and to determine further data needed from site investigations. This work culminated in the advanced conceptual design that was published in 1996 (CRWMS M&O 1996a).

DOE has now begun the last cycle of site characterization at Yucca Mountain. With input based on the repository design and TSPA results, the Secretary of Energy will decide in 2001 whether to recommend the site to the President. If the Secretary of Energy recommends the site and the recommendation is accepted according to the process described in Section 1.9, DOE will develop the LA and submit it in 2002 to NRC for authorization to construct a monitored geologic repository.

NRC regulations in 10 CFR 60 require DOE to initiate a performance confirmation program

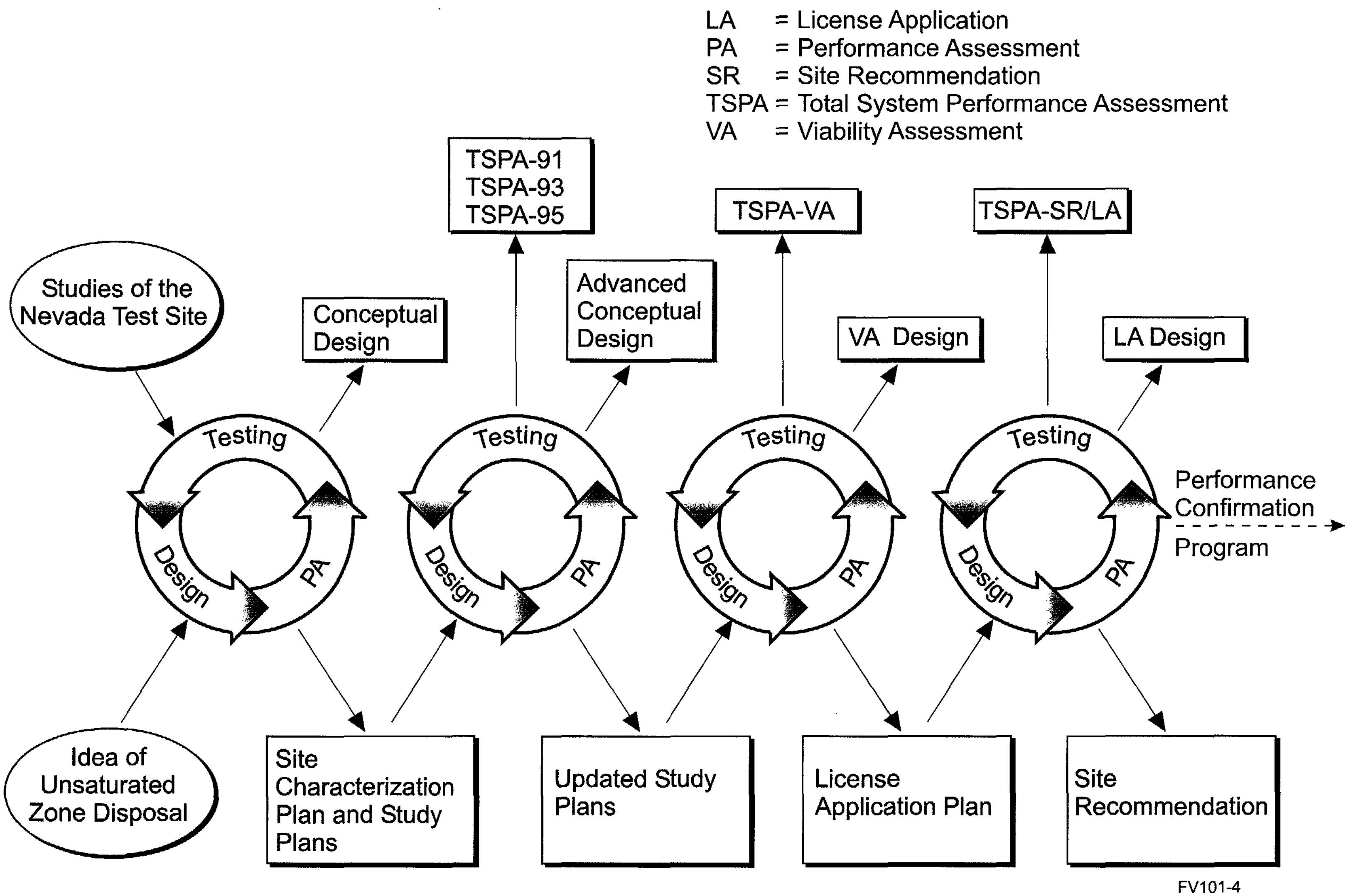



Figure 1-4. Site Characterization Process

during the site characterization phase and to continue the performance confirmation program until the repository is permanently closed. This activity also is shown in Figure 1-4 and is discussed in Section 1.8.1.5.

## 1.8 PREPARING FOR THE LICENSE APPLICATION

Volume 4 provides the plan and describes the remaining work required to complete an LA. Volume 4 describes both the remaining technical (science and engineering) work and the related statutory and support activities that are necessary to complete a site recommendation and an LA.

The technical work DOE has planned includes that work needed to complete a postclosure safety case, preclosure safety case, and other work needed for a complete LA. Because these three technical work elements are important themes that run throughout the VA, they are summarized in the following sections.

### 1.8.1 Formulation of the Postclosure Safety Case

To obtain a license from NRC to construct a monitored geologic repository at Yucca Mountain, DOE must demonstrate reasonable assurance that waste can be disposed of without unreasonable risk to the health and safety of the public [10 CFR 60.31(a)]. The challenge in licensing a monitored geologic repository is that compliance with this safety standard must be ensured for many thousands of years. DOE is addressing the uncertainties that are associated with such long-term assessments of repository performance by developing a set of data and analyses that, collectively, are intended to provide the reasonable assurance that a successful LA will require. DOE refers to this set of data and analyses as the postclosure safety case. As planned, the postclosure safety case will consist of the following five elements:

1. Assessment of expected postclosure performance and supporting evidence
2. Design margin and defense in depth
3. Consideration of disruptive processes and events
4. Insights from natural and man-made analogs
5. A performance confirmation plan

The scope of each element of the postclosure safety case is summarized below.

DOE is developing the elements of the postclosure safety case within the framework of a repository safety strategy (DOE 1998). The repository safety strategy describes how a repository at Yucca Mountain is expected to contain radioactive wastes for thousands of years and ensure that radiation doses to persons living near Yucca Mountain would not exceed regulatory limits. By providing a conceptual model of how the natural and engineered barrier systems would work together to meet the postclosure performance objectives, the repository safety strategy provides a framework for integrating site information, repository design information, and performance assessment results. This, thereby, provides a framework for identifying the information needed to complete the postclosure safety case.

The repository safety strategy identifies four key attributes of an unsaturated repository system that are important to meeting postclosure performance objectives. From performance assessment studies (Volume 3, Section 6.4), DOE has identified 19 principal factors of greatest importance to postclosure performance, which are associated with the four key attributes. The key system attributes of the repository safety strategy and the associated 19 principal factors are listed in Table 1-2.

DOE uses the repository safety strategy to identify information needs and to prioritize planned work by considering the relative importance of each principal factor to estimated repository performance, what is known now about each principal factor, and what more can be learned about each principal factor. Volume 4, Section 2.2.4, details the application of this approach. As the 19

Table 1-2. Key Attributes of the Repository Safety Strategy and Principal Factors Affecting Postclosure Performance for the Reference Repository Design

| Key Attributes of the Repository Safety Strategy | Principal Factors |
|---|---|
| Limited water contacting waste packages | Precipitation and infiltration of water into the mountain |
| | Percolation of water to depth |
| | Seepage of water into drifts |
| | Effects of heat and excavation on water flow |
| | Dripping of water onto waste packages |
| | Humidity and temperature at waste packages |
| Long waste package lifetime | Chemistry of water on waste packages |
| | Integrity of outer waste package barrier |
| | Integrity of inner waste package barrier |
| Low rate of release of radionuclides from breached waste packages | Seepage of water into waste packages |
| | Integrity of spent nuclear fuel cladding |
| | Dissolution of uranium oxide and glass waste forms |
| | Solubility of neptunium |
| | Formation and transport of radionuclide-bearing colloids |
| | Transport through and out of engineered barrier system |
| Radionuclide concentration reduction during transport from the waste packages | Transport through unsaturated zone |
| | Flow and transport in saturated zone |
| | Dilution from pumping |
| | Biosphere transport and uptake |

principal factors reflect, in part, the VA reference design, and as DOE is still evaluating design options and alternative designs, the repository safety strategy includes the identification and performance of the additional work needed to select the repository design for the site recommendation and LA.

Implementation of the repository safety strategy and the resultant repository system is intended to provide the basis for each element of the postclosure safety case. That is, implementation of the repository safety strategy will result in a repository system that has acceptable expected postclosure performance, accounts for potential disruptive processes and events, and includes engineered features that enhance performance and reduce the importance of uncertainties of the natural system by employing design margin and defense in depth. The last two elements of the postclosure safety case—insights from natural and man-made analogs and a performance confirmation plan—will serve to provide additional assurance that the natural and engineered features of the repository system will function as intended and anticipated.

The five elements of the postclosure safety case, listed in the previous section, are briefly described in the following sections.

#### 1.8.1.1 Element 1: Assessment of Expected Postclosure Performance and Supporting Evidence

The current assessment of expected performance is summarized in Volume 3. That assessment reveals that the vast majority of the radionuclides in the repository are not mobile at the Yucca Mountain site; they are insoluble or they sorb strongly to minerals and materials in the repository and cannot move out of the repository. However, a very small fraction is relatively mobile and could be transported away from the repository if contacted by water, subject to attenuation and retardation by the various barriers incorporated into the repository. This issue is mitigated for this small fraction if water is kept from contacting the waste in the first place.

Current data and analyses indicate that the Yucca Mountain site provides favorable features for limiting the contact of water with the waste. Its location in an semiarid region, and the nature of the site, limit the amount of water that can reach the repository level to a small fraction of the precipitation at the ground surface (approximately 5 percent for current climate conditions) (Section 2.2.3.2). The site provides a thick unsaturated zone (Section 2.2.3.2) where the waste can be placed deep below the surface and yet well above the water table. Because of the thickness of the unsaturated zone, the waste packages would be protected from changes in conditions at the surface while still being kept well away from groundwater. The site would, therefore, provide predictable and stable environments for design of engineered barriers that can further limit the exposure of waste to water.

Performance assessment studies show that, in addition to the natural barriers, engineered barriers would keep water away from the waste for thousands of years. They indicate, for example, that the highly corrosion-resistant inner container and the thick steel outer container (as specified in the reference design of this VA) will provide effective barriers against water for different conditions that will occur during the postclosure performance period (see Section 5.1.2 of Volume 2). Although some issues must still be addressed, the estimates indicate that robust waste packages could be designed to remain intact for thousands of years in the repository environments. The studies also indicate that the spent nuclear fuel cladding would likely provide an additional barrier to water contacting the waste, even if both the outer and inner waste package barriers were to be breached.

These conclusions follow in part from performance assessment analyses of expected future behavior of the repository system and sensitivity studies of the factors contributing to this behavior. Volume 3 presents the most recent set of DOE performance assessment analyses. These are based on assessment of all available data on processes and conditions that might occur and on the likelihood of occurrence. Models of these processes and conditions are used to estimate the performance of the system in numerical simulations. These simulations provide one important method of assessing the site's ability to contain and isolate waste for many thousands of years and are useful as a means to assess the relative contributions of various factors. However, the results of the computational models should not be interpreted as a precise prediction of the actual performance of the repository. As described in Volume 3, significant uncertainty in the detailed results of performance assessment is inevitable because of spatial and temporal variability of both site conditions and the complexity of coupled physical processes that will operate in the repository environment.

#### 1.8.1.2 Element 2: Design Margin and Defense in Depth

Because there will always be uncertainties in estimates of repository performance over many thousands of years, DOE is not relying solely on these estimates to demonstrate reasonable assurance that the postclosure performance standards will be met. Design margin and defense in depth provide important additional assurance.

Design margin refers to the standard engineering practice of including margins of safety in specifications for engineered components to account for uncertainty in the conditions to which the components will be subjected and for variability in the properties of component materials. Defense in depth is the term used to describe the property of a system of multiple barriers to mitigate uncertainties in conditions, processes, and events by employing barriers that are redundant and independent: failure in any one of them does not result in failure of the system. A specific feature of the reference design that provides defense in depth is the use of two waste package containment barriers with different corrosion modes.

Defense in depth will be accomplished though the use of multiple engineered barriers in conjunction with the natural barriers. The environments in which the engineered barriers will perform have been investigated during years of site characterization, so that comprehensive evaluation of design alternatives, including design features that would provide defense in depth, can be conducted. DOE will evaluate these to ensure that alternatives to the design have been considered before finalizing the reference design.

#### 1.8.1.3 Element 3: Consideration of Disruptive Processes and Events

To demonstrate reasonable assurance that public health and safety will be protected, estimates of repository performance under expected conditions must be accompanied by analyses of disruptive processes and events that could affect the site. At Yucca Mountain, these include tectonics and seismicity, volcanism, inadvertent human intrusion, and nuclear criticality (Volume 3, Section 4.4).

#### 1.8.1.4 Element 4: Insights from Natural and Man-Made Analogs

Natural analogs refer to geologic systems that exhibit evidence of natural processes that could be relevant to long-term repository performance. A direct analog for a Yucca Mountain repository does not exist; however there are sites that can provide information on processes and conditions relevant to a repository system at the site. Natural analog studies may provide information that bears on the transport of radionuclides over extended periods and distances that cannot be duplicated in laboratory or field experiments. Natural analogs can also provide information on the effect of various environmental conditions on materials that are intended to have a long life.

Man-made analogs, similarly, may provide information regarding relevant processes or materials over time scales and distances that are not reproducible in a laboratory or in limited-duration field studies. For example, examination of ancient ceramic human artifacts might provide useful information about the stability of candidate ceramic materials for drip shields or waste package coatings.

Natural analogs have significant limitations, including the incomplete and heterogeneous geologic record, uncertainty in characterizing the past conditions under which the processes took place, partial or imperfect analogy to repository conditions, and divergent interpretations of geologic data. However, as a supplement to site characterization and predictive modeling of repository performance, natural analogs offer the advantage of direct study of relevant processes over long time periods and extended spatial scales applicable to repository performance. Furthermore, data acquired from analog studies, which may provide independent verification of the reasonableness of the assessments of repository performance, are generally independent of site characterization and modeling studies conducted for Yucca Mountain.

#### 1.8.1.5 Element 5: A Performance Confirmation Plan

NRC regulations (10 CFR 60, Subpart F) require that a performance confirmation program be started during site characterization and continue until permanent closure of the repository. The DOE performance confirmation program is documented in the *Performance Confirmation Plan* (CRWMS M&O 1997b). This plan will be updated as needed and is intended to contribute to reasonable assurance at the time of LA submittal by defining, in advance, the tests that will be conducted during the preclosure period to accomplish the following:

- Confirm that subsurface conditions encountered during construction, waste emplacement operations, and monitoring are within the ranges assumed in the LA.
- Confirm that natural and engineered systems and components are functioning as intended and anticipated.
- Evaluate compliance with NRC postclosure performance requirements.
- Evaluate readiness for permanent closure.

The parameters and concepts identified for performance confirmation will be based on the understanding of natural and engineered barrier processes available when the LA is submitted. Uncertainties regarding many of these processes will remain at the time of submittal. Therefore, the plan will describe the process to integrate new information that will be gained during the construction, operation, and monitoring periods.

### 1.8.2 Formulation of the Preclosure Safety Case

A monitored geologic repository must be designed to protect public health and safety during the preclosure waste emplacement and monitoring phase, as well as during the long-term, postclosure phase. However, unlike the case for the postclosure period of performance—for which there is no NRC licensing precedent and for which there are unique systems and unique issues—there are many applicable codes, standards, and NRC regulatory guidance documents and many years of industry experience in the operation of nuclear facilities that can be applied directly to preclosure repository design and operations.

The preclosure safety case (Volume 4, Section 2.3.1) will demonstrate compliance with the requirements of 10 CFR 60.21(c)(3), 10 CFR 60.135, and 10 CFR 60.136 for the performance of the monitored geologic repository during preclosure operations. Elements of this case will be based on a comprehensive safety analysis that identifies facility operations and waste emplacement scenarios from which design basis events; safety classification of structures, systems, and components; and system safety criteria are developed. The strategy for developing the preclosure radiological safety case enables the development of the repository system design and subsystem performance requirements to focus on those high priority features that are important to radiological safety. The preclosure radiological safety case will include an evaluation of the radiological exposure consequences at the site boundary and the occupational worker consequences of the examined design basis events as mandated by 10 CFR 60.

Preclosure radiological safety will be provided by a combination of prevention and mitigation of events that could cause exposure to radiation in excess of regulatory limits. Prevention is the use of features to ensure that the frequency of such events is minimized or eliminated. Mitigation is the use of features to ensure that public and occupational worker exposures are held within 10 CFR 60 and 10 CFR 20 limits for a given design basis event. The risk (combination of frequency and consequences) of a radiological release can be reduced by decreasing the occurrence frequency of an event sequence (i.e., prevention) and/or by decreasing the consequences of the event sequence (i.e., mitigation). Some design and operating features provide measures of both prevention and mitigation to reduce the risk of an event.

The preclosure radiological safety strategy for each operational function will include primary safety and defense-in-depth features. Primary radiological safety features are those that are determined by design basis event analyses to be required to meet 10 CFR 60 and 10 CFR 20 requirements. Defense-in-depth features are those that are present or included to provide additional safety margins to reduce the overall safety risk of the facility.

The preclosure radiological safety case will allocate event and consequence prevention and mitigation functions to the facility based on its operational functions. The primary safety features (either prevention or mitigation) to satisfy the preclosure radiological safety functions will be augmented by diverse and independent defense-in-depth features. The selection and reliance upon primary and defense-in-depth features will be determined by the design basis event analyses.

### 1.8.3 Other Work Needed to Complete a License Application

An important component of the program that remains to be completed is selection of the repository design to support the site recommendation and LA. This effort is related to the formulation of both the postclosure and preclosure safety cases. DOE will examine an appropriate and comprehensive range of alternative design features and concepts before selecting the reference design to support site recommendation and the subsequent LA. Such an evaluation is an appropriate precursor to submittal of the LA to ensure that reasonably different approaches have been considered and because NRC regulations require a comparative evaluation of alternatives to major design features that are important to waste isolation. Design features and alternative design concepts have been developed to identify design studies needed to support the selection of the initial site recommendation and subsequent LA design.

Design studies supporting the development and evaluation of design options, design features, and alternative design concepts will allow DOE to select a design to be carried forward to support site recommendation and LA. This selection will be based on strategies for licensing approach, design margin, and defense in depth, as well as a strategy for addressing uncertainty. In work that is underway and will continue into fiscal year 1999, these options, design features, and alternatives will be more fully developed and their performance and projected cost will be evaluated.

While formulation of the postclosure and preclosure safety cases and selection of the reference repository design are the main focus of the remaining testing, design, and performance assessment work, there is a substantial body of other work that also is required to support the site recommendation and, if the site is recommended and the recommendation is accepted, submittal of an LA. This other work includes development of the draft and final EISs, as shown in Figure 1-1, and an evaluation of the suitability of the site under DOE siting guidelines. There are many required prelicensing activities including interactions with NRC staff to resolve issues, preparation of topical reports and other licensing documents, technical data management, records management, and development of an integrated electronic information system that will use internet technology to allow NRC to access DOE records and data. The remaining site characterization work requires continuation of construction and operation activities in the field and maintenance of the existing field infrastructure. Other support activities include information management, quality assurance, project management, institutional interactions, administrative services, and training support. These activities are detailed in Volume 4 along with the work related to developing the postclosure and preclosure safety cases.

## 1.9 REPOSITORY MILESTONES AFTER THE VIABILITY ASSESSMENT

The key repository milestones that follow the VA are shown in Figure 1-1.

DOE plans to submit a draft EIS in 1999 and a final EIS in 2000 to support the site recommendation decision in 2001. Section 114 of the Nuclear Waste Policy Act of 1982 requires DOE to prepare a final EIS to accompany any recommendation to the President to approve the Yucca Mountain site. The EIS is to be prepared in accordance with the requirements of the National Environmental Policy Act of 1969, except where the Nuclear Waste Policy Act of 1982 specifies exemptions to those requirements. DOE will prepare the EIS by following its National Environmental Policy Act implementing procedures in 10 CFR 1021.

The Nuclear Waste Policy Act of 1982 requires that the Secretary initiate the site recommendation by holding public hearings near the Yucca Mountain site for the purpose of informing residents of the area of such consideration and receiving their comments regarding the possible recommendation of the site. The Secretary must then decide whether or not to recommend the site to the President. If the Secretary decides to recommend the site, this recommendation must be accompanied by preliminary NRC comments concerning the extent to which the site characterization analysis and the waste form proposal seem to be sufficient for inclusion in the LA. DOE must also submit the views and comments of the governor and legislature of any state, or the governing body of any affected Indian tribe, together with the Secretary's response to such views.

As noted earlier, if the President accepts the recommendation, the President will submit the recommendation to Congress. The Nuclear Waste Policy Act of 1982 provides for a process whereby the recommendation then can be disapproved by Congress or by the State of Nevada. If the State of Nevada disapproves the recommendation, the disapproval can be overridden by a joint resolution of Congress. If the President recommends the site and the recommendation is permitted to take effect, DOE will submit an LA to NRC for authorization to construct the repository.

The Nuclear Waste Policy Act of 1982 directs NRC to adopt, to the extent practicable, the final DOE EIS in connection with the issuance by NRC of a construction authorization and license for a repository. Compliance with procedures of the Act is deemed adequate consideration of the need for a repository, the time when a repository is available, and all alternatives to the isolation of high-level radioactive waste and spent nuclear fuel in a repository. Further, DOE need not consider alternate sites for a repository.

As shown in Figure 1-1, the site recommendation decision is scheduled for 2001 and submittal of an LA for 2002. The NRC decision to authorize construction is scheduled for 2005, at the earliest, consistent with the direction in the Act that NRC issue its decision on construction authorization within three years of submittal of an LA. Repository construction would begin upon receipt of this authorization. DOE must update its LA and submit it to NRC before NRC will issue a license to receive and possess nuclear waste. This update is scheduled for 2008. Assuming repository construction sufficient to begin waste emplacement will take 5 years, the first waste emplacement at Yucca Mountain could occur in the year 2010.

The Nuclear Waste Policy Act of 1982 requires a geologic repository to be designed and constructed to permit retrieval of the spent nuclear fuel emplaced in the repository, during an appropriate period of operation, for any reason pertaining to public health and safety or to the environment, or to permit recovery of economically valuable contents of the spent nuclear fuel. The NRC repository licensing regulation (10 CFR 60) requires that a geologic repository be designed for waste retrieval starting any time up to 50 years after initiation of waste emplacement operations, unless a different time period is approved or specified by NRC. Compliance with these requirements means that the repository must be designed to be kept open for some number of years after the last waste has been emplaced.

Future generations will decide how long to maintain the repository in an open, monitored condition, whether to retrieve the waste, and when to permanently close the repository. These decisions will be based on scientific and societal considerations and will be made by local and national governments, including representatives of the State of Nevada and other areas or groups that may be affected by the repository. To ensure that future decision makers have flexibility regarding these decisions, DOE is designing the repository with the capability to be closed as early as approximately 10 years after emplacement of the last waste package or to be kept open for at least 100 years after initiation of waste emplacement, with a reasonable expectation that the repository could actually be kept open, with appropriate maintenance, for 300 years after initiation of waste emplacement. To reflect this decision to design the repository to accommodate an extended period of monitoring, DOE has adopted the phrase *monitored geologic repository* to refer to the prospective nuclear waste disposal facility at Yucca Mountain. The VA assumes a reference case in which closure of the monitored geologic repository is initiated in 2110, one hundred years after initiation of waste emplacement operations.

# 2. CHARACTERISTICS OF THE YUCCA MOUNTAIN SITE

Characteristics of the natural system at Yucca Mountain, such as its semiarid climate and deep water table, led in part to its current consideration as the setting for a geologic repository for high-level radioactive waste. These characteristics provide an environment that potentially could isolate the waste from the effects of water for long periods. Capitalizing on those characteristics, DOE has identified several lines of evidence to show that a repository at Yucca Mountain would protect the health and safety of the public over the long term. These lines of evidence, described in Section 1.8.1, form the postclosure safety case.

The postclosure safety case depends on limiting the amount of water that comes in contact with waste, using waste package materials with long lifetimes, retarding the movement of any radionuclides that are eventually released, and reducing radionuclide concentration as they move away from the repository. In addition, the postclosure safety case requires that disruptive events, such as volcanic eruptions, earthquakes, criticality, and human intrusion, have either a low likelihood of occurring or that their effects will not compromise the safety of a repository. Because of these dependencies, an adequate understanding of the natural system is needed to demonstrate the validity of the safety case through assessments of repository long-term performance. An understanding is also needed to design engineered barriers that work in concert with the natural system and to show that a repository can be operated safely during the preclosure period.

This section describes the current understanding of the natural system at Yucca Mountain and provides a basis for identifying the work that still needs to be carried out. It supports the technical basis underlying the preliminary design concept for a repository and waste package (see Volume 2, "Preliminary Design Concept for the Repository and Waste Package"). It also supports a quantitative assessment of long-term repository performance (see Volume 3, "Total System Performance Assessment"). While much is known about Yucca Mountain's natural features, DOE plans to continue conducting characterization studies to reduce key uncertainties and to provide additional information needed to support the preclosure and postclosure safety cases. Volume 4, "License Application Plan and Costs," describes the additional work planned to support a decision on the site recommendation and prepare a license application should the recommendation be approved.

In addition to supporting the preliminary design concept and assessment of long-term performance, information presented in this section also shows the degree to which the NRC key technical issues (NRC 1997a) can be addressed (see also Volume 4, Section 4.3.3). NRC factors each key technical issue into subissues that more narrowly focus the technical points to be addressed. Issue resolution status reports prepared by NRC indicate that, for a number of subissues related to the natural environment, there are no outstanding questions at this time. For the remaining issues, work planned over the next several years will build on current knowledge to provide the additional information needed to address them, support a site recommendation, and, if the recommendation is approved, demonstrate compliance with NRC requirements for a geologic repository.

Information on Yucca Mountain site characteristics is summarized from the *Yucca Mountain Site Description* (CRWMS M&O 1998d), which comprehensively reports current knowledge about the site and its surrounding region. Details and background on the current findings for Yucca Mountain, which are beyond the scope of this document, are found in the *Yucca Mountain Site Description.*

Mineral exploration studies of the Yucca Mountain region date back to the early 1900s. In the 1950s, investigations supporting nuclear weapons testing at the Nevada Test Site provided information on the region's geologic, hydrologic, and geophysical characteristics. In the late 1970s, as interest grew in Yucca Mountain as a possible site for a geologic repository, additional studies were initiated focusing on the site hydrogeology and geology. With the enactment of the Nuclear Waste Policy Act in 1982, and its amendment in 1987, Yucca Mountain characterization studies gained additional momentum.

In accordance with the Nuclear Waste Policy Act, as amended, DOE prepared the site characterization plan (DOE 1988c) for Yucca Mountain. This comprehensive plan identified studies that DOE intended to carry out to determine whether a geologic repository at the Yucca Mountain site should be recommended. Over the years, investigation results, the availability of new scientific methods, and reductions in annual funding beginning in fiscal year 1996 have led to modifications of the original plan. Changes to the original plan are documented in semiannual progress reports that DOE submits to NRC and to the governor and legislature of the State of Nevada, as required by the Nuclear Waste Policy Act. This plan, with the changes noted in the progress reports, has served as the basis for Yucca Mountain investigations over the past 10 years.

Both surface-based and underground investigations have been used to characterize the Yucca Mountain site. Surface-based studies have included the following:

- Mapping geologic structures, including rock units, faults, fractures, and volcanic features
- Monitoring earthquake activity
- Using gravitational, magnetic, electrical, and seismic methods to infer the distribution and properties of geologic units and structures at depth
- Heating a large block of rock to observe the subsequent effects of heat on its hydrologic and chemical properties
- Drilling boreholes into the mountain to identify the geologic units present at depth, measuring the depth of the water table and properties of the hydrologic system, observing the rate at which water moves from the surface into the rock below, and determining air and water movement properties above the water table

As an example of work that has been carried out, Figure 2-1 shows the distribution of boreholes that have been drilled to support Yucca Mountain characterization studies.

Underground testing has also helped characterize the Yucca Mountain site. Excavating a 7.9-km (4.9-mile) tunnel (Exploratory Studies Facility Main Loop) that dips down into the mountain, extends along its length, and then rises back up to the surface (see Figure 2-2) facilitated this testing. Seven alcoves were constructed off the tunnel to implement tests, including those examining the hydrologic behavior of various geologic features and units. Mapping the excavations provides data on the distribution of geologic units and on the character of faults and fractures. One of the underground alcoves is also the site of in situ thermal tests investigating how heat affects the mechanical behavior of the local rock, the movement and chemistry of water, and the geochemical makeup of the rock and minerals deposited along fractures. These experiments also provide data to understand how thermal, mechanical, hydrologic, and geochemical processes are coupled. A new cross-drift tunnel is currently being excavated to allow additional characterization of the mountain.

Laboratory testing has augmented the surface and underground tests carried out at the site. Studies at laboratories allow properties and processes to be investigated under controlled conditions. Laboratory tests include those to determine mechanical, chemical, and hydrologic properties of rock samples in support of repository design and development of process models. Tests also provide properties of radionuclides that affect their transport if released from a repository. Additional laboratory tests include those to examine the chemical properties of ambient water samples and the effects of heat on behavior and chemical properties of water in the host rock.

Investigations conducted to date provide information allowing the preliminary design of a repository and waste package that will work in concert with Yucca Mountain's natural system to enhance waste isolation. Current results also permit analyses of the long-term performance of a potential repository to evaluate its ability to protect the public's health and safety. Uncertainties remain, however, and

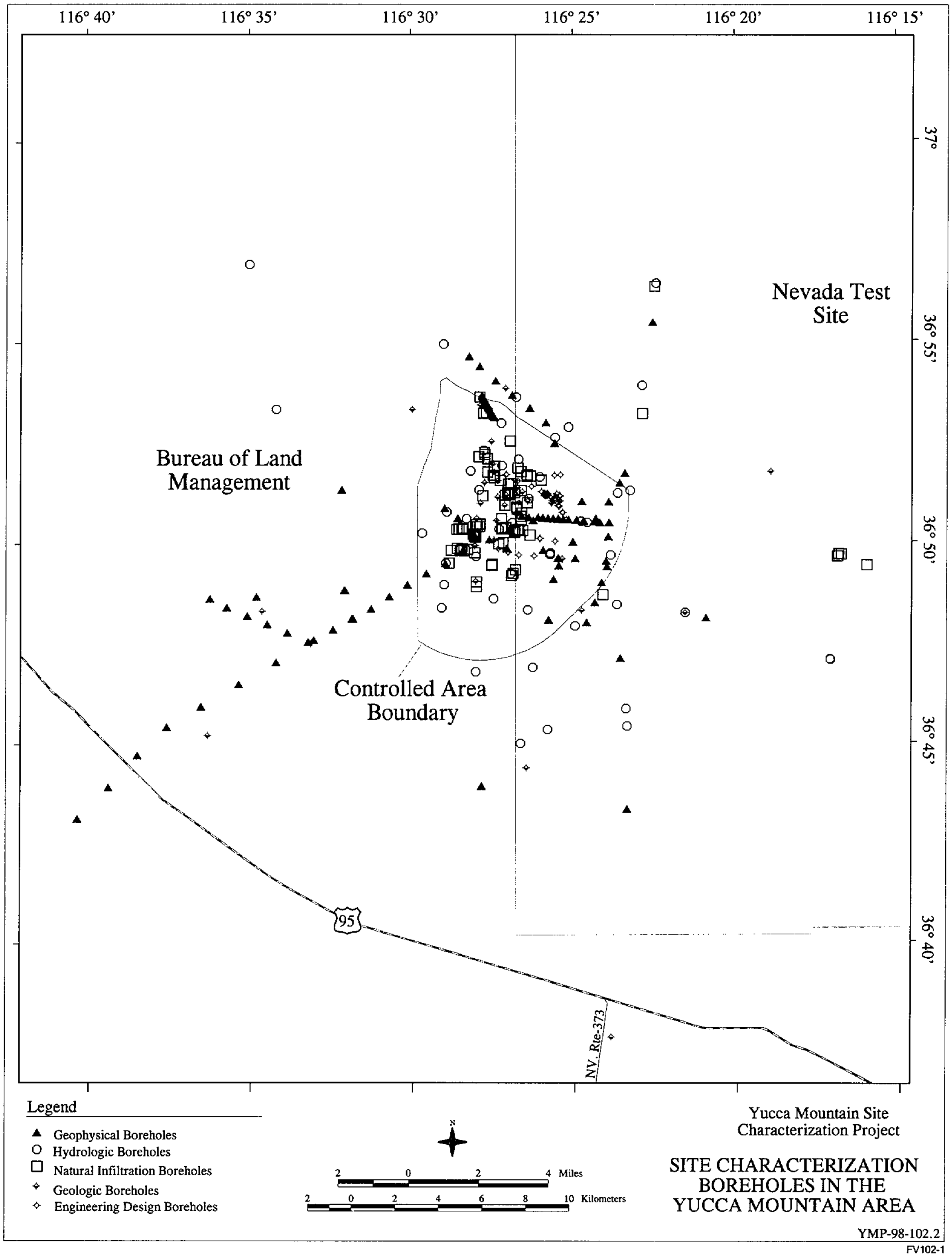



Figure 2-1. Boreholes Drilled to Characterize the Yucca Mountain Vicinity

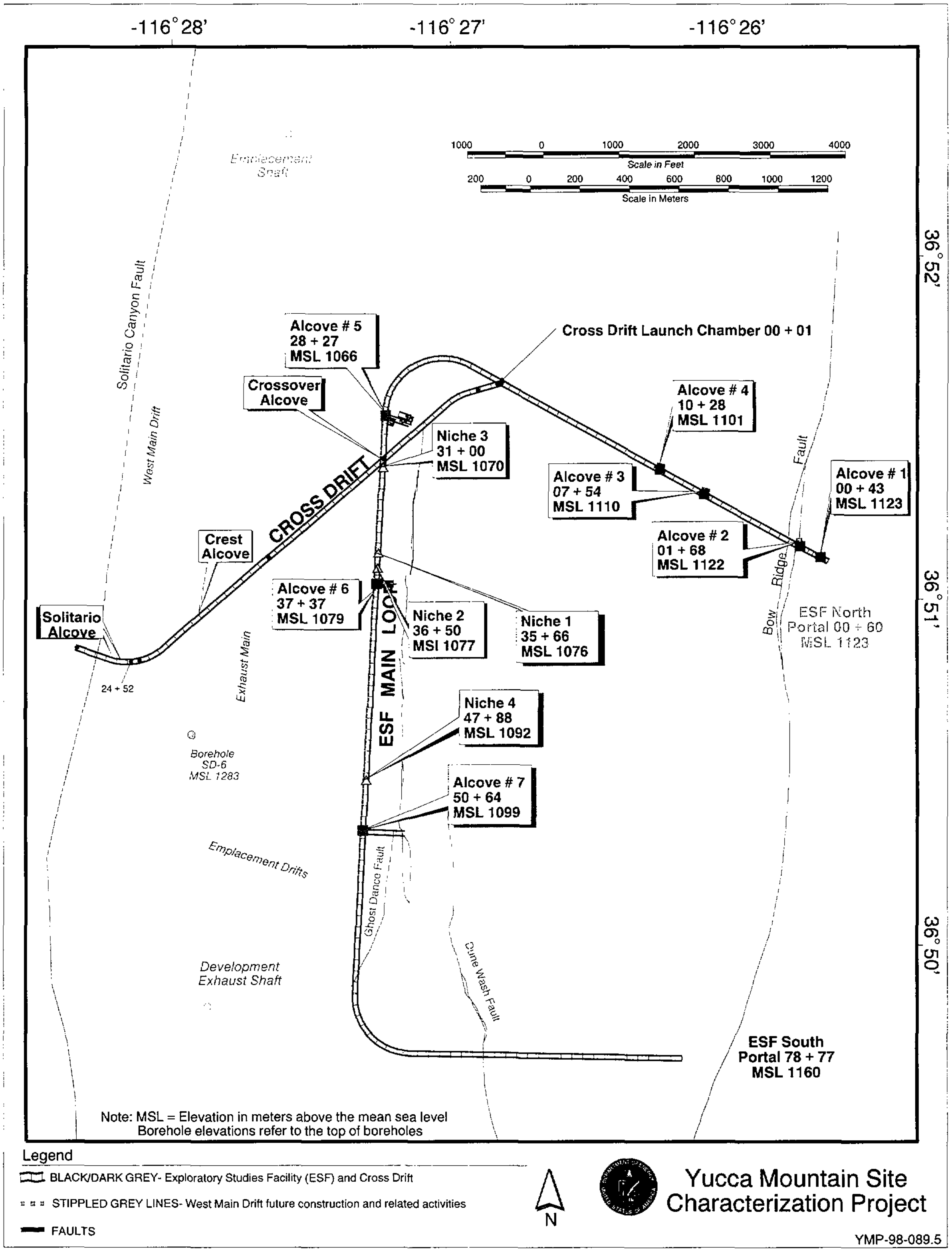



Figure 2-2. Exploratory Studies Facility and Cross-Drift

additional studies are needed to support a decision on whether a repository system at the site should be recommended and to prepare the LA. These additional investigations are discussed in Volume 4.

## 2.1 OVERVIEW OF SITE INVESTIGATION FINDINGS

Collecting Yucca Mountain site characterization data greatly enhances knowledge of the site and its vicinity as it relates to potential repository suitability. This section summarizes current site investigation findings; more detailed information and references are found in Section 2.2 and in the *Yucca Mountain Site Description* (CRWMS M&O 1998d).

Geologic studies based on extensive mapping, borehole sampling, geophysical surveying, laboratory measurements, and observations in the underground Exploratory Studies Facility have defined the distribution of stratigraphic units, provided information on their physical, hydrological, and geochemical properties, and located major and minor geologic faults at the site. Scientists have combined this information to form an integrated geologic site model that supports proposed repository design and performance assessment. This integrated model also provides a framework for continuing site investigations.

Gaining climate and meteorological information also helps determine potential repository performance. Climate determines local rainfall, the amount of water that is available to filter into the mountain, and the vegetation that grows at Yucca Mountain (which influences water movement into the mountain). Climate also influences the amount of water that enters the hydrologic system and the elevation of the local water table. Climate investigations have focused on understanding long-term cycles and how the climate near the mountain has changed over the past several hundred thousand years. Regional data from several sites show that the local climate reflects observed worldwide climate cycles. Data on past climates can also be used to predict the likely range of precipitation and temperature for future climates at Yucca Mountain. During the current climate, annual precipitation averages about 170 mm (7 in.) per year and temperatures range from over 40°C (104°F) on summer days to below 0°C (32°F) during winter nights. Current climate characteristics like those observed near the mountain have prevailed approximately 20 percent of the time over the past several hundred thousand years. Climate at Yucca Mountain over the next tens of thousands of years is expected to be wetter and cooler than today. Scientists estimate that during these wetter and cooler periods, the average amount of precipitation may double or triple.

The postclosure safety case for a repository relies on the complementary characteristics of the site and the engineered barriers to limit the amount of water that could contact waste packages placed inside Yucca Mountain. Therefore, an adequate understanding of Yucca Mountain's hydrologic system is needed to design a repository that works in concert with the natural surroundings. Studies of the hydrologic system at Yucca Mountain have focused on water infiltration from precipitation at the surface, water percolation through the unsaturated zone (above the water table), and water flow in the saturated zone (below the water table). A model of site infiltration under present climate conditions shows an average rate of about 8 mm (0.3 in.) per year and ranges from 0.0 mm (0.0 in.) per year in some local washes to 40 mm (1.6 in.) per year in the northwestern part of Yucca Mountain. For possible future climate conditions, model results indicate that the average annual net infiltration may increase by a factor of 7–20.

The rate at which water percolates through the mountain has been studied using data from surface-based boreholes and from the Exploratory Studies Facility. Estimates of percolation flux vary as a function of location and according to the method used. Results from the various studies range from about 0.1 to 21.1 mm (0.004 to 0.83 in.) per year with an average rate of about 7 mm (0.3 in.) per year. Other investigations of percolation indicate that water moves through most geologic units of the mountain primarily along interconnected fractures; movement through the rock matrix represents a secondary effect although it is important in some units. A numerical model of flow through the unsaturated zone incorporates information on the geologic framework and rock hydrologic properties. The model is adjusted and refined using saturation and water potential data, gas pressures and gas flow rates, ambient temperature and heat flow data, locations and hydrochemistry of perched water bodies, and environmental isotope concentrations and water ages. The model indicates that percolation flux at the proposed repository level varies spatially and ranges from approximately 1–20 mm (0.04–0.8 in.) per year.

The saturated zone also plays a role in the postclosure safety case for a repository, acting to reduce the concentration of radionuclides in groundwater during transport. Saturated zone characterization has included mapping water table levels to better understand flow dynamics. Mapping the water table has identified a large gradient to the north of Yucca Mountain and a smaller gradient to the west. Past water table levels below Yucca Mountain were apparently no more than 100 m (328 ft) higher in cooler, wetter climates. Borehole tests provide information on the transmissivity of the tested intervals and on the anisotropy of saturated zone flow. Data on the tendency of water to flow from one aquifer to another show that water does not tend to flow from the overlying volcanic aquifers to the underlying carbonate aquifer. Therefore, any radionuclides released from a Yucca Mountain repository that reach the volcanic aquifers beneath the site would not be expected to enter the deeper regional aquifer.

The current assessment of expected performance for a geologic repository reveals that most radionuclides have a low mobility in the Yucca Mountain environment (see Volume 3). Current geochemical studies focus on those radionuclides with greater mobility and the tendency of underlying rock formations to impede transport towards the accessible environment. Researchers have collected information on the distribution of minerals throughout the strata forming Yucca Mountain and on those found along fractures where most of the water might flow. Three principal minerals or groups of minerals are key barriers against possible radionuclide migration: zeolites (clinoptilolite, mordenite, and chabazite), clay (smectites), and magnesium oxides. Studies have also addressed how readily radionuclides dissolve in water and, how once in water, they tend to become attached to minerals encountered along the flow path. Scientists have incorporated this information into those transport models used to assess site performance. Geochemical studies also provide information on the environment into which waste packages will be emplaced and on the spatial distribution of minerals that may affect repository construction because of health concerns.

If the site is recommended and approved, and a license is granted, construction of a repository and emplacement of waste would necessarily alter the natural system. The alteration would result from the introduction of engineered materials and from heat generated by the waste. These effects would cause changes in the geomechanical, geohydrological, and geochemical systems within the near field and altered zone. Some of the changes could be temporary and would probably be reversed as the waste-generated heat dissipates. Other changes could be permanent.

The heat generated by the waste could affect the geohydrologic regime in the near field by causing boiling conditions for hundreds to thousands of years. This could temporarily produce zones of dried-out rock, zones in which condensation would occur, and zones with relatively low humidity. These effects would probably influence the amount of liquid water contacting waste (as a function of time after emplacement). Geochemical processes affected by the heat could include mineral dehydration, dissolution and precipitation of minerals, and changes in local water chemistry.

Geologic testing shows that thermal loading would probably cause the near-field rock to expand and alter the stress on the rock. Increases in compressive stress may induce rockfalls within the drifts and may alter the hydrologic flow system by closing or opening fractures. Temperature increases are also associated with decreases in rock strength. The introduction of man-made materials to the near-field environment may also modify the chemical environment and influence geochemical reactions. Present, past, and future studies evaluating these effects assess their impacts on potential site performance.

Geologic studies have also addressed the likelihood of future tectonic events disrupting the proposed repository. Data collected on the spatial distribution of faults and volcanic centers, and on the history of these features, are being used to estimate future volcanic eruptions and earthquakes. Volcanic and fault displacement hazards at Yucca Mountain are low; however, the hazard from earthquake ground motion at Yucca Mountain is potentially significant, and facility design will need to be able to resist seismic shaking. Finally, the potential for the existence and economic development of Yucca Mountain's natural resources has been assessed and determined to be low; it is unlikely that Yucca Mountain would be targeted as a future exploration site.

## 2.2 DESCRIPTION OF THE SITE

Yucca Mountain is located in southern Nevada approximately 100 miles (161 km) northwest of Las Vegas. The mountain is an irregularly shaped volcanic upland varying in elevation at its crest from 1,500 m to 1,930 m (4,921 ft to 6,332 ft) and characterized by approximately 650 m (2,132 ft) of relief. The area surrounding the site includes Nye, Lincoln, Esmeralda, and Clark counties in Nevada and Inyo county in California. The site occupies land controlled by three federal agencies: the U.S. Air Force (Nellis Air Force Range), DOE (Nevada Test Site), and the U.S. Bureau of Land Management (BLM) (Figure 2-3). Nearly all the area surrounding Yucca Mountain is federally owned, and very little is developed or urban land (Figure 2-3). A large percentage of the land around Yucca Mountain is anticipated to remain federally owned or withheld from public use in the future.

The natural system at Yucca Mountain—including its geological, climatological, hydrological, and geochemical components—plays a key role in the repository safety strategy. Characteristics of the natural system, such as the thick unsaturated zone and low infiltration of water, are key factors limiting the amount of water available to contact waste packages. This contributes to a long lifetime for waste packages remaining intact and, therefore, a very slow degradation of the waste form within the package and an extremely gradual release of radionuclides. Even after radionuclides begin escaping the waste packages, the natural system will reduce their concentration during transport away from the repository, thereby limiting possible exposure to the public. Thus, adequate knowledge of the natural system is essential to making an informed decision about the suitability of a potential repository at Yucca Mountain for the nation's high-level radioactive waste and spent nuclear fuel.

Population density near Yucca Mountain is low (Nevada State Demographer 1998a and 1998b). Population distribution studies supporting the preclosure safety case cover an area 50 miles (80 km) in radius following Regulatory Guide 1.109 (NRC 1977). The distribution and population density within this area are shown in Figure 2-4. Nye County, which encompasses the site, has 0.59 persons per square kilometer (1.53 persons per square mile). Of the total population of 27,460 in Nye County, 69 percent live in the unincorporated town of Pahrump, 70–80 km (43–50 miles) south-southeast of Yucca Mountain. Overall population density in Lincoln County is 0.15 persons per square kilometer (0.39 persons per square mile). Larger concentrations of population are found in Clark County to the southeast, in the incorporated and unincorporated areas of the Las Vegas valley.

In the remainder of this section, natural system characteristics are briefly described. First, the components of the current system are discussed. Then, the effects of waste-generated heat and potential repository construction materials are addressed. Finally, current understanding of potentially disruptive natural events, such as earthquakes, is discussed. A detailed discussion of the natural system can be found in the *Yucca Mountain Site Description* (CRWMS M&O 1998d).

### 2.2.1 Geologic Framework

The natural system includes a group of interdependent subsystems, including geological, climatological, hydrological, and geochemical systems. By describing the distribution and characteristics of rock units at the site, a geologic framework can be defined for relating and correlating the properties, ambient conditions, and future behavior of the other subsystems. The understanding of site geol-

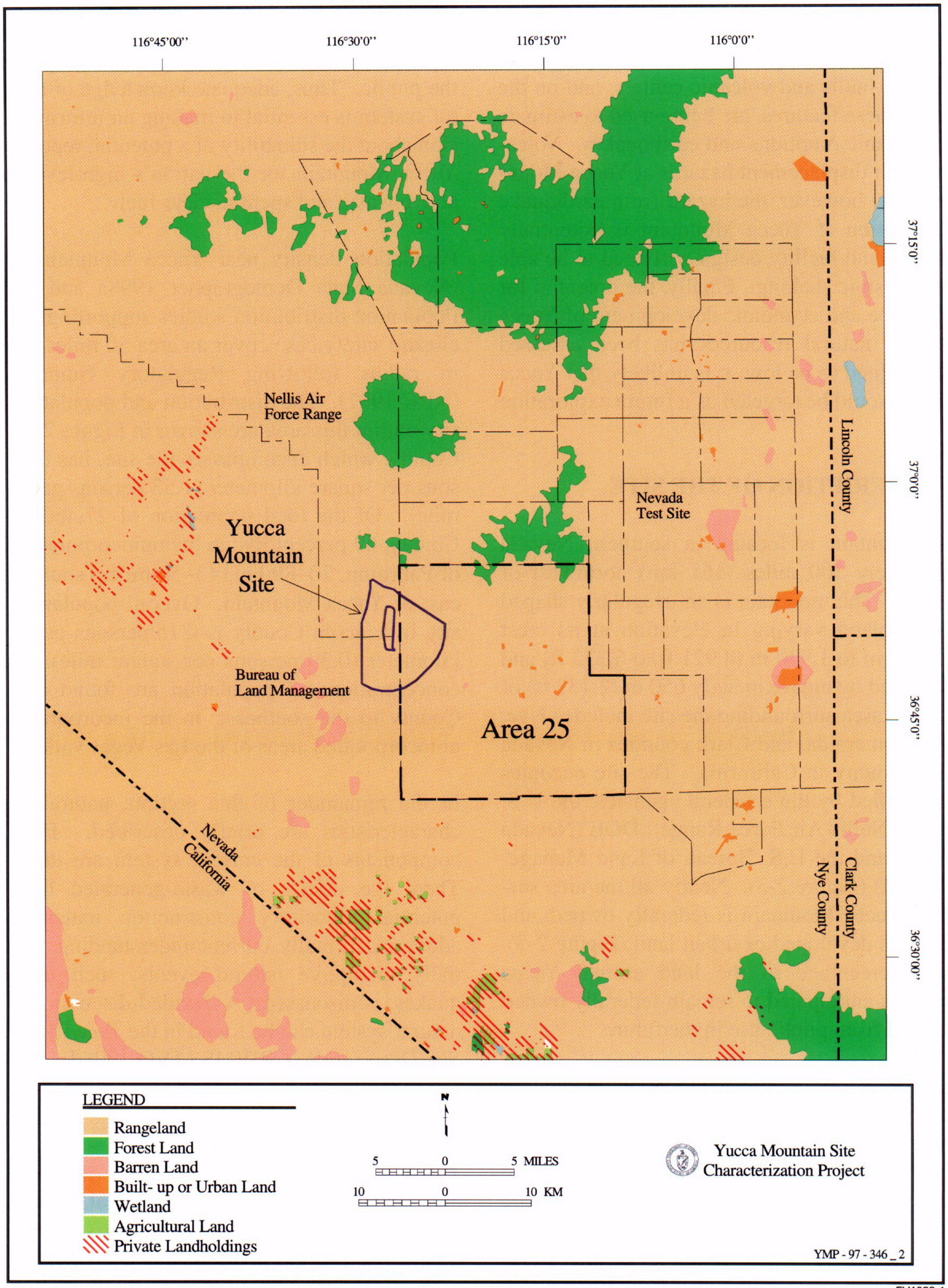



Figure 2-3. Land Use in the Vicinity of Yucca Mountain



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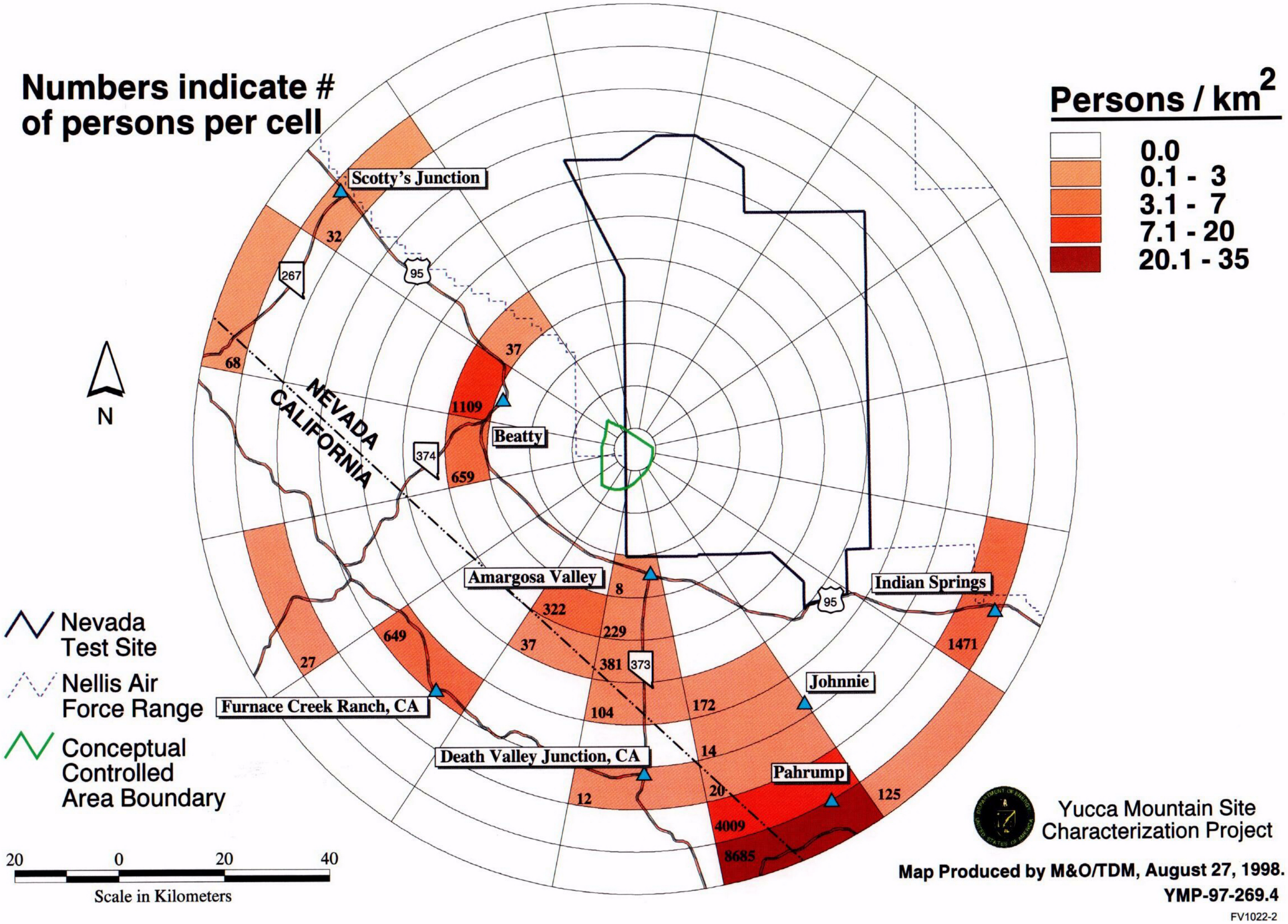



Figure 2-4. Population Density in the Vicinity of Yucca Mountain



C-02

ogy has evolved following years of extensive studies, resulting in the construction of a detailed, integrated site geological model (CRWMS M&O 1997e) containing stratigraphic and structural relationships as well as rock property and mineralogical data.

This section describes the geology of the Yucca Mountain site and region, with an emphasis on those site aspects that are most relevant to regulatory issues, design, and performance assessment of the proposed repository. By providing the underlying framework for all site characterization activities, the results help to address NRC's key technical issues. These issues are discussed in more detail in Volume 4, Section 4.3.3.

#### 2.2.1.1 Regional Setting

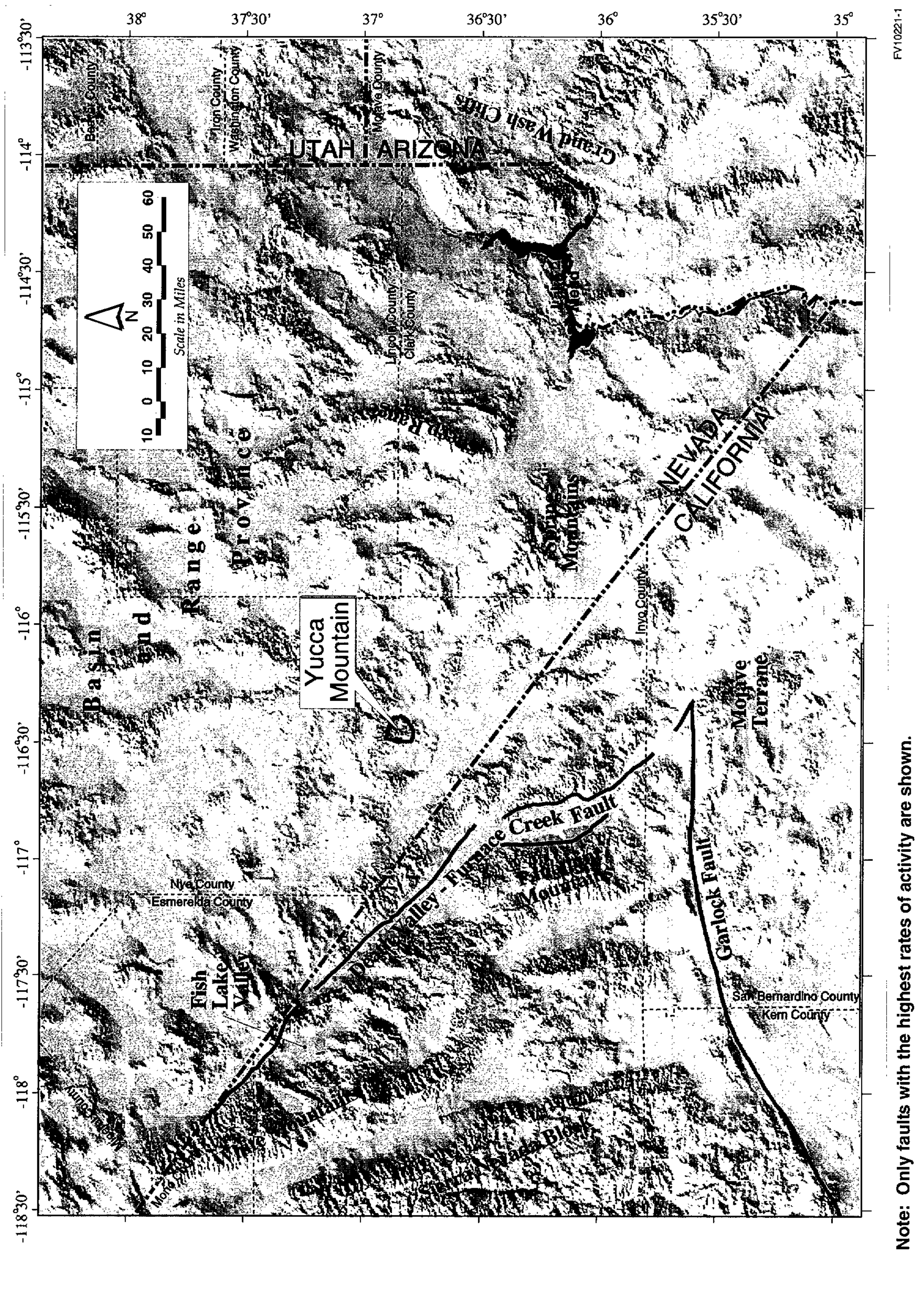
As shown on Figure 2-5, Yucca Mountain is in the Basin and Range province of the western United States within the region known as the Great Basin. The Great Basin encompasses nearly all of Nevada and parts of Utah, Idaho, Oregon, and California. The mountain ranges of the Great Basin are mostly north-south aligned, tilted, fault-bounded blocks that may extend more than 80 km (50 miles) in length and are generally 8–24 km (5–15 miles) wide. Relief between valley floors and mountain ridges is typically 300–1,500 m (984–4,921 ft), and valleys occupy approximately 50–60 percent of the total land area. The valleys are filled with thick deposits of alluvium derived from erosion of the adjacent ranges. The ranges are separated north and south by roughly 25–30 km (15–19 miles), but many ranges arc toward each other and merge together. This pattern is the result of generally east-west-directed crustal extension that began in the Tertiary period and continues at present (Hamilton 1988). As a result of plate tectonics, the crust on the western edge of the Basin and Range (the Sierra Nevada) has been moving to the west relative to the east edge (the Wasatch Front in central Utah). Rocks of every age, from very old (Precambrian) to recent (Pleistocene), have been deformed by this extension. The extension has caused complex faulting, resulting in ranges composed of tilted fault blocks bounded by major range-front faults. Seismic reflection geophysical studies show that this style of deformation extends beneath the intervening basins, where it is buried by alluvium (Brocher et al. 1998; Hauge et al. 1987).

Yucca Mountain is also influenced by a structural domain known as the Walker Lane (Figure 2-6), which extends north-westward from Las Vegas, subparallel to the Nevada-California border, into California. The Walker Lane is a structural belt characterized by northwest-trending right-lateral faults and northeast-trending left-lateral faults (Stewart 1988). Walker Lane tectonic activity probably originated in the late Oligocene period (approximately 25–30 million years ago) as a result of northwest-directed extension (Stewart 1988).

The rocks composing Yucca Mountain are part of the southwestern Nevada volcanic field. This field was formed by the eruption of large volumes of volcanic rocks from multiple sources to the north. Figure 2-6 shows the location of several calderas (volcanic centers) and the widespread extent of volcanic deposits.

The highest rate of modern tectonic activity in the southwestern Great Basin (i.e., active faulting and volcanism) is found in the Inyo-Mono domain to the west and south of Yucca Mountain, which includes the Furnace Creek-Death Valley fault zone, the Sierra Nevada front, and the area north of the Garlock fault (Figure 2-5). This domain includes modern basins and ranges with great structural relief, including Death Valley Basin and the Panamint Range. Because of its ongoing tectonic activity and exposure of deep-seated crustal rocks, the Inyo-Mono domain is an important part of the regional geologic setting.

**Regional Stratigraphy.** The lithology (rock type) and stratigraphy (the sequence in which rocks were deposited) of the regional geologic setting provide the basis for understanding the geologic history and evolution of the area, which is fundamental to analyzing geologic hazards such as those associated with earthquakes and volcanoes. Also, by controlling the regional flow of groundwater, the various rock types would directly control the




**Note: Only faults with the highest rates of activity are shown.**

Figure 2-5. Physiographic Map of the Southern Basin and Range Province

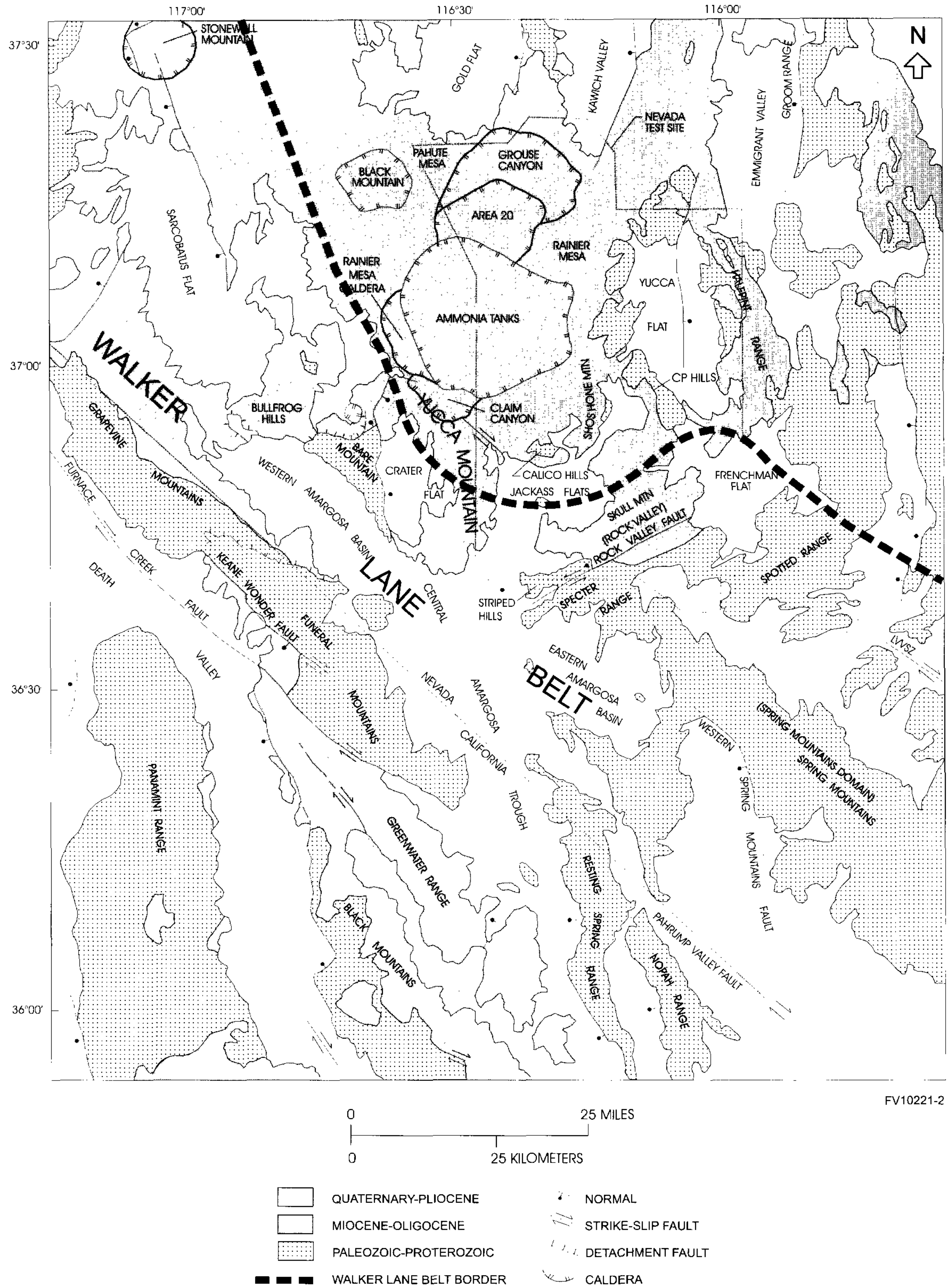



Figure 2-6. Generalized Geologic Map of the Yucca Mountain Region
(Source: CRWMS M&O 1998d)

migration of any potential releases from the repository. Figure 2-6 shows the distribution of rock types in the region. Finally, the stratigraphy and lithology provide the framework for understanding more local aspects of the Yucca Mountain site, including its structural geology and tectonics, geoengineering properties, mineral resource potential, hydrology, and geochemistry. The following summary briefly describes rock units important to the regional geologic setting of Yucca Mountain:

- **Precambrian Era.** Precambrian rocks (greater than approximately 570 million years in age) include two major rock types: an older, metamorphosed basement assemblage and a younger, metasedimentary assemblage. Both groups tend to retard the flow of groundwater except where extensive faulting or fracturing is present. Water that has reacted with rocks of this group can typically be identified by isotopic geochemical techniques (Peterman and Stuckless 1993) that may indicate regional groundwater flow paths.

- **Paleozoic Era.** Paleozoic rocks (rocks ranging from approximately 570 million to 240 million years in age) in the Yucca Mountain region include lower (older) carbonate strata (limestone and dolomite); a middle, fine-grained shale, siltstone and sandstone unit; and an upper (younger) carbonate unit (limestone). The carbonate units form important aquifers throughout southern Nevada (Winograd and Thordarson 1975).

- **Mesozoic Era.** Strata from this era (rocks ranging from approximately 240 million to 66 million years in age) are generally absent near Yucca Mountain. Regionally, these strata are dominantly continental and shallow marine sediments (sandstones and siltstones) with minor Cretaceous granitic plutonic rocks. Structurally, the Mesozoic was a period of active tectonic activity characterized by regional compression.

- **Cenozoic Era.** Cenozoic rocks (66 million years in age to the present) near Yucca Mountain fall into three groups. The last two are of major importance to the Yucca Mountain site:

  - Pre-middle Miocene (greater than about 16 million years old) sedimentary rocks

  - Mid-to-late Miocene (15 million to 7.5 million years old) volcanic rocks that constitute the southwestern Nevada volcanic field, including Yucca Mountain

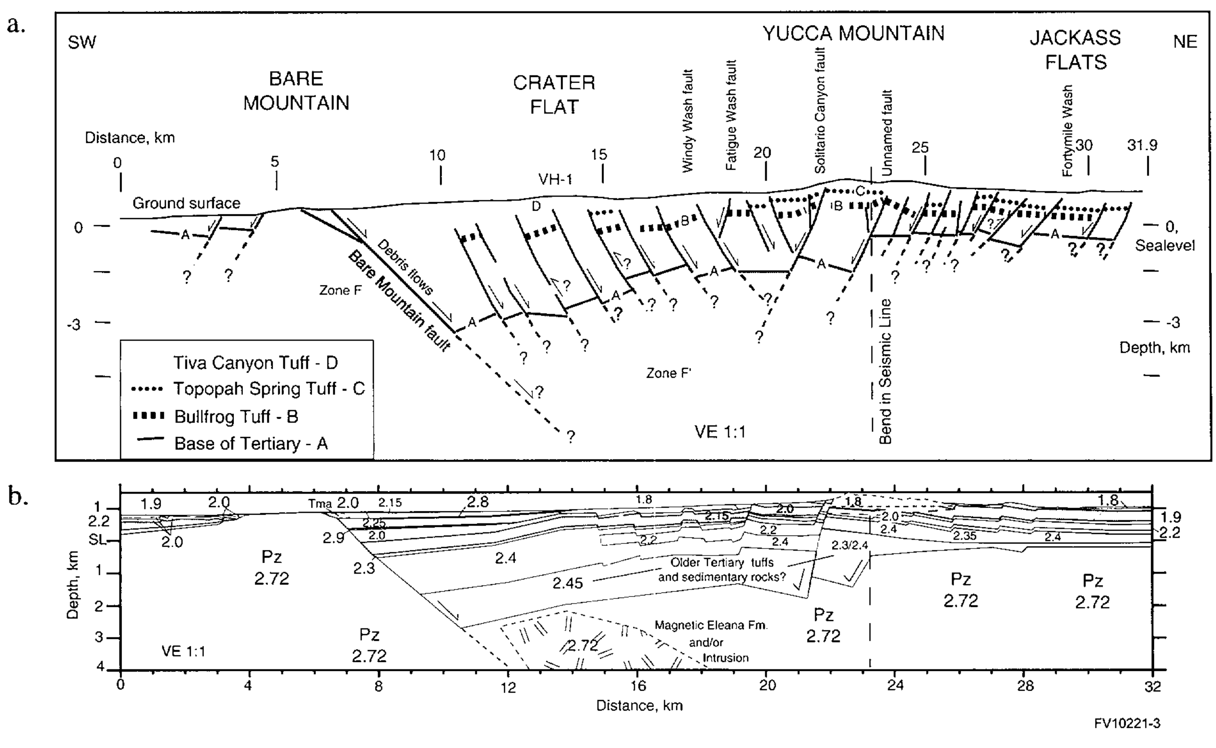
  - Plio-Pleistocene (3.7 million years old to modern) basalts and basin sediments

The explosive volcanism that culminated in the formation of the southwestern Nevada volcanic field is the most significant depositional event of the Cenozoic era near Yucca Mountain. This event formed six major calderas (volcanic centers) between 15 million and 7.5 million years ago (Sawyer et al. 1994). This event also created the rocks of Yucca Mountain, and brought to a close the major regional tectonic activity that created the present Yucca Mountain geologic setting (Figure 2-6). The succession of tuff and lava units forming Yucca Mountain are described further in Section 2.2.1.2 (Site Bedrock Geology).

The most recent deposits in the region consist of alluvial sediments, formed during highland erosion, and infrequently erupted basaltic volcanic rocks. The basaltic eruptions represent a continuation of the activity during the mid- to late-Miocene epoch (Crowe et al. 1995). Following an episode 3.7 million years ago, a subsequent basaltic eruption occurred between 1.7 million and 0.7 million years ago consisting of four cinder cones (Little Cone, Red Cone, Black Cone, and Makani Cone) aligned north-northeast along the Crater Flat axis. The final episode of basaltic volcanism created the Lathrop Wells Cone, which includes fissure eruptions, spatter and scoria cones, and basaltic lava flows. Satellite spatter cones at the east base of the main cone have a northwest alignment. The Lathrop Wells Cone complex is approximately 75,000 years old (CRWMS M&O 1998d).

**Regional Tectonic Models.** Several alternative tectonic models have been proposed to explain the known structural, volcanic, and seismic characteristics of the site (Whitney 1996, Chapter 8). The models provide a means for integrating and understanding data such as the history of volcanism, deposition of sediment, and fault movement in the site vicinity. In assessing volcanic and earthquake hazards, scientists considered a range of models in evaluating the likelihood of future events (see Section 2.2.7). NRC considers the evaluation of tectonic models and crustal conditions as a subissue of the Structural Deformation and Seismicity Key Technical Issue (NRC 1997a) (see Volume 4, Section 4.3.3.2). Although uncertainty still remains with respect to a tectonic model for Yucca Mountain, the uncertainty can be accommodated in probabilistic hazard assessments (and no further work is planned to refine the tectonic model by the project).

Figure 2-7 is an east-west cross section showing the results of regional geophysical studies and interpreted structural relations from Bare Mountain to Jackass Flats (Brocher et al. 1998). The top of the figure shows an interpretation based on seismic reflection data that is consistent with gravity data that are modeled by the layers and rock densities shown below in grams per cubic centimeter. Yucca Mountain is believed to be part of a down-dropped block bounded on the west by the steeply eastward dipping Bare Mountain fault. Beneath Crater Flat, the block is segmented by eastward dipping faults; beneath Yucca Mountain and Jackass Flats, generally westward dipping faults are interpreted. The block-bounding faults of Yucca Mountain (e.g., the Solitario Canyon, Bow Ridge, Paintbrush Canyon, and Windy Wash faults) and the Bare Mountain fault appear to be discrete, planar faults, at least some of which may descend to the base of the Earth's brittle crust. At deep crustal levels, the faults could provide a path for basaltic magma




Source: Brocher et. al (1998)

Figure 2-7. Conceptual East - West Cross Section of the Yucca Mountain Vicinity from Bare Mountain to Jackass Flats: a) Interpretation, b) Rock Density Model (values in g/cm$^3$; Pz—Paleozoic rocks) intrusion, so volcanic and seismic events may in some cases be coupled.

### 2.2.1.2 Site Bedrock Geology

The characteristics of the rocks that would host the potential repository are important to virtually all aspects of repository design and performance assessment. The repository safety strategy is dependent on thoroughly understanding not only ambient site conditions, but also how the natural system would respond to conditions induced by facility construction and operation. System performance modeling requires knowledge of the hydrologic and transport properties of the rocks above, below, and in the repository horizon. Modeling also requires understanding how properties may be modified by the coupled thermal, hydrologic, mechanical, and geochemical processes that could occur following waste emplacement. Repository design relies on a thorough understanding of the geoengineering properties and thermal response of the units into which waste emplacement drifts (tunnels) would be excavated. Figures 2-8 and 2-9 are a simplified geologic map and cross section, taken from Day et al. (1997) showing geologic relations at a repository scale. The stratigraphic, structural and rock properties data have also been combined to form an integrated site geologic model for use in performance assessment and design (CRWMS M&O 1997e).

**Stratigraphy.** The entire sequence at Yucca Mountain is composed of Mid-Tertiary volcanic rocks formed by eruptions of ash or magma from volcanic vents to the north (Sawyer et al. 1994; Buesch et al. 1996). The eruptive centers were in some ways similar to modern environments near Yellowstone National Park, Wyoming, or Long Valley, California, which are currently active volcanic regions. All of the individual units, therefore, get progressively thinner from north to south. Most of the rocks are ash flow tuffs, which are formed when a hot mixture of volcanic gas and ash violently erupts and flows at high velocity over the landscape. As the ash settles, it is subjected to various degrees of compaction and fusion depending on temperature and pressure. If the temperature is high enough, glass shards are compressed and fused to produce a welded tuff (a hard, brick-like rock with very little open pore space in the rock matrix). Non-welded tuffs, compacted and consolidated at lower temperatures, are less dense and brittle, and they have higher porosity. Airfall tuffs are formed from ash cooled in the air before reaching the ground, and bedded tuffs are composed of ash that has been reworked by stream action.

The performance of the proposed repository would be dependent on the characteristics of the rocks that affect movement of water from the surface to the repository, from the repository to the water table, and in the saturated zone below the water table, where any released radionuclides could be transported. Therefore, this section focuses on the rocks in that portion of the stratigraphic section. Figure 2-10 depicts the major units within the Yucca Mountain section, which include (from the top down) the Paintbrush Group, composed of the Tiva Canyon tuff and the Topopah Spring tuff, the Calico Hills Formation, and the Crater Flat Group. The width of the column schematically representing each unit indicates the degree of welding. At even greater depth, pre-Tertiary rocks, including the Paleozoic carbonate aquifer, are also present. Additional discussion of the hydrologic properties of the rocks is presented in Sections 2.2.3 and 2.2.4.

**Paintbrush Group.** The Tiva Canyon tuff is a large-volume, regionally extensive ash flow tuff that comprises most of the rocks exposed at the surface of Yucca Mountain. The unit is divided into two members: a lower crystal-poor member and an upper crystal-rich member, which each have a characteristic geochemical composition: the lower member is a rhyolite, and the upper member is a quartz-latite (Sawyer et al. 1994). Rhyolites have a higher percentage of silicon and alkali elements and a lower percentage of aluminum, iron, calcium, and magnesium than quartz-latites. The thickness of the formation ranges from less than 50 m to as much as 175 m (165 to 575 ft).

The Yucca Mountain tuff below the Tiva Canyon varies in thickness from 0 to 77 m (0 to 253 ft) and is nonwelded to partially or densely welded where it is thickest in the northern and western parts. Although typically vitric (composed of shards of volcanic glass), the tuff is increasingly devitrified

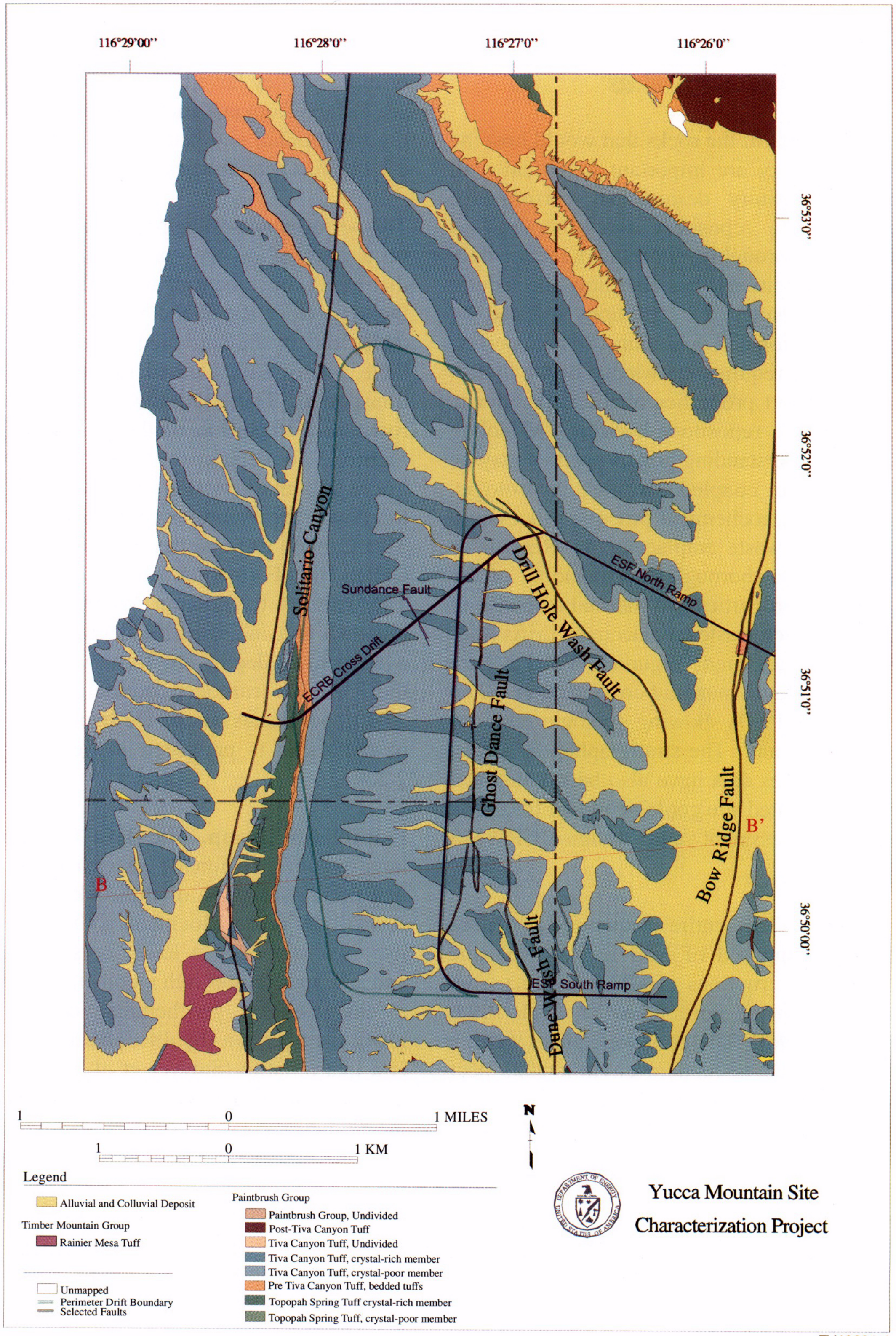



Figure 2-8. General Bedrock Geology of the Central Block Area, Yucca Mountain, Nevada (Source: Day et al. 1997)



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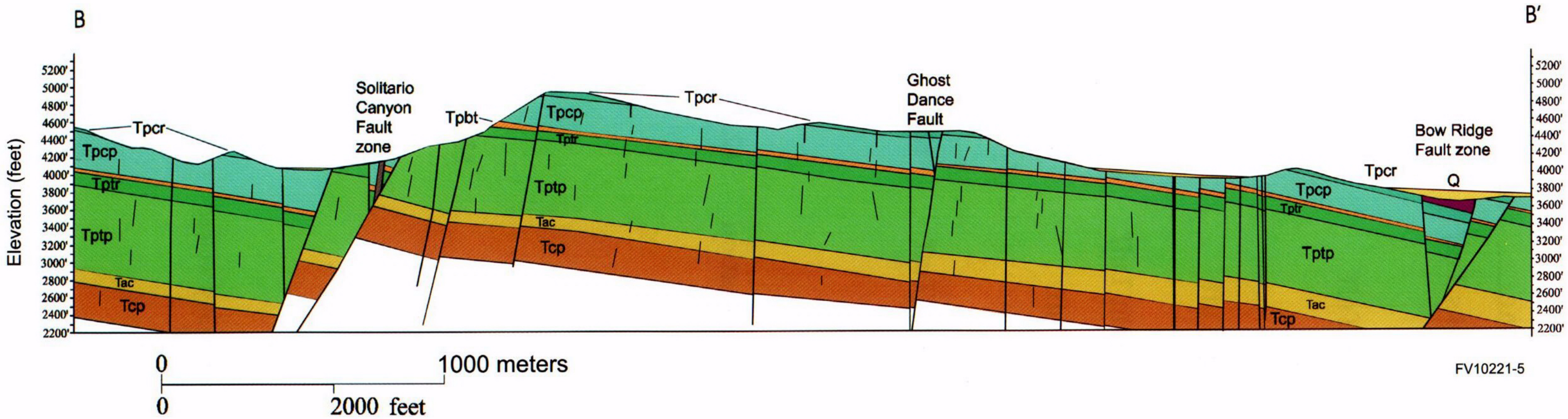


Legend:

Alluvial and Colluvial Deposit (Q)

Timber Mountain Group

Rainier Mesa Tuff (Tmr)

Paintbrush Group

Tiva Canyon Tuff, crystal-rich member (Tpcr)

Tiva Canyon Tuff, crystal-poor member (Tpcp)

Pre-Tiva Canyon Tuff bedded tuffs (Tpbt)

Topopah Spring Tuff, crystal-rich member (Tptr)

Topopah Spring Tuff, crystal-poor member (Tptp)

Calico Hills Formation (Tac)

Crater Flat Group

Prow Pass Formation (Tcp)

Figure 2-9. Simplified Geologic Cross Section of Yucca Mountain, West to East
(Source: Day et al. 1997)

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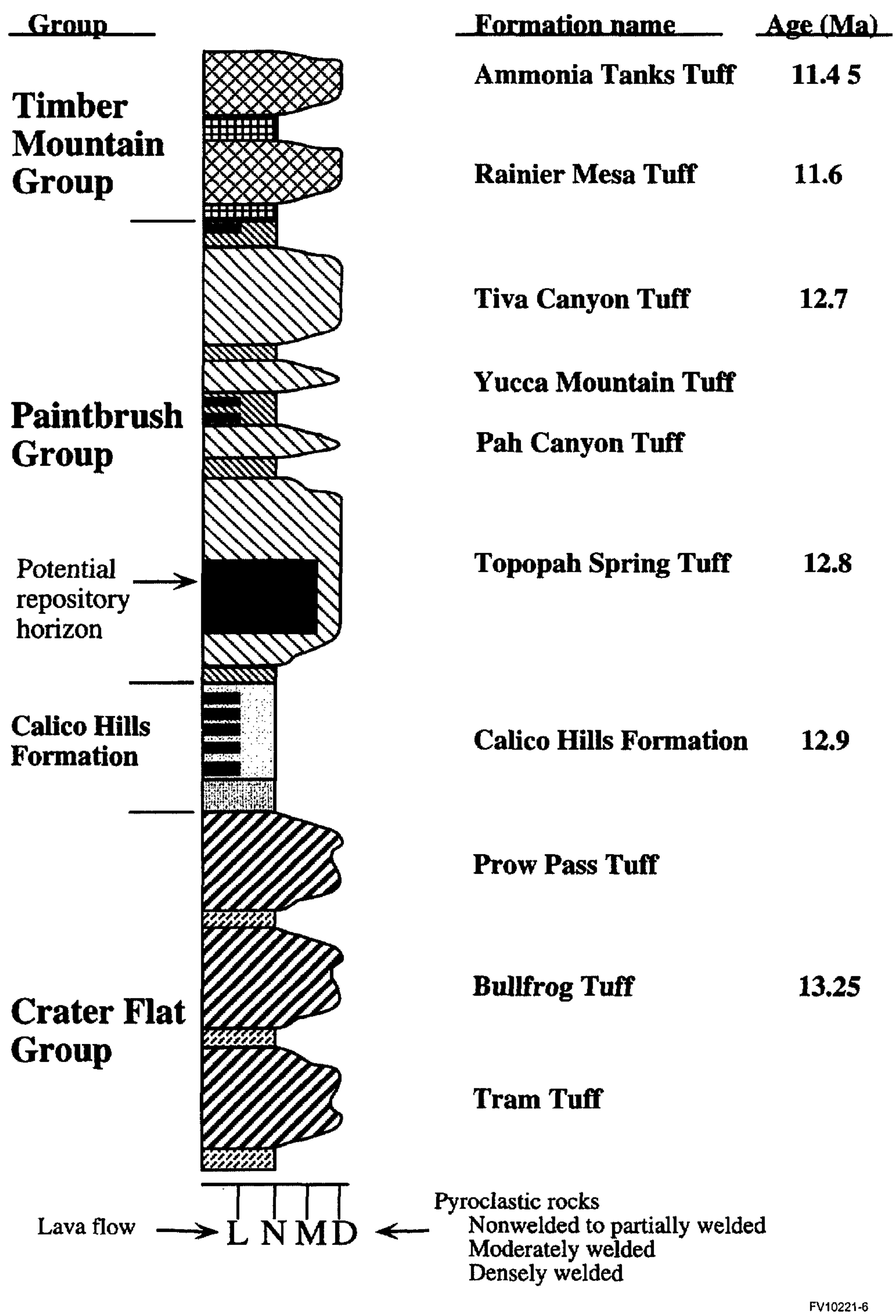


Note: Width of column indicates degree of welding for pyroclastic rocks.

Figure 2-10. Principal Rock Stratigraphic Units at Yucca Mountain
(Source: CRWMS M&O 1998d)

where it is thick. (Glass shards are altered to fine grained silica and clay minerals.) A bedded airfall tuff sequence up to 15 m (49 ft) thick may overlie the Yucca Mountain tuff (Diehl and Chornack 1990, p. 47).

The Pah Canyon tuff occurs beneath the Yucca Mountain tuff and has a maximum thickness of about 70 m (230 ft) in the northern part of Yucca Mountain and thins southward to zero (Moyer et al. 1996). The Pah Canyon tuff varies from nonwelded to moderately welded and contains vitric pumice fragments preserved in a nondeformed matrix. Bedded tuffs may also occur below the Pah Canyon tuff.

The lowermost unit in the Paintbrush Group is the Topopah Spring tuff, which is the host rock for the potential repository. The Topopah Spring tuff has a maximum thickness of about 350 m (1,148 ft) near Yucca Mountain (Buesch et al. 1996). Like the Tiva Canyon tuff, the Topopah Spring tuff is compositionally zoned from a lower crystal-poor, high-silica rhyolite to an upper crystal-rich quartz latite. Each member is divided into numerous zones and subzones based on depositional feature variations such as crystal content and assemblage, size and abundance of pumice and rock fragments, distribution of welding and crystallization zones, and fracture characteristics. The crystal-poor member is divided into a vitric zone near the base and devitrified rocks of the lower nonlithophysal, lower lithophysal, middle nonlithophysal, and upper lithophysal zones. Lithophysae are voids in the rock caused by bubbles of volcanic gases trapped in the rock matrix during cooling. The nature, size and abundance of lithophysae in the tuffs are important because they may affect the mechanical and hydrologic properties of the rock. These last three zones, divided on the basis of their lithophysal content, comprise the potential repository horizon. All of these units are strongly welded. A portion of the vitric zone at the base of the Topopah Spring tuff, commonly referred to as the vitrophyre, is an important thermal-mechanical unit and a locally important hydrologic unit.

The upper crystal-rich member (greater than 10 percent crystals, or phenocrysts) is also divided into lithophysal, nonlithophysal, and vitric zones. Rocks in both the lithophysal and nonlithophysal zones are devitrified and strongly welded. The tuff is capped by a vitric unit distinguished by the preservation of volcanic glass forming rocks with a vitreous luster.

**Calico Hills Formation.** The Calico Hills Formation is a series of rhyolite tuffs and lavas resulting from an episode of volcanism approximately 12.9 million years ago (Sawyer et al. 1994). Five separate ash flow units, overlying a bedded tuff unit and a locally occurring basal sandstone unit, have been distinguished. The formation thins southward, from a total thickness of 289 m (948 ft) north of the repository block, to 41 m (135 ft) to the south.

Several characteristics of the Calico Hills Formation are particularly significant to repository performance models. None of the Calico Hills ash flows are strongly welded; therefore, the rocks have much lower strength than the Topopah Spring tuff (they are less brittle and hard), and they generally have higher porosities. Because of their lower strength, the fractures that are ubiquitous in welded tuffs are rare or absent in the Calico Hills. In fact, surface and borehole observations indicate that highly fractured Topopah Spring tuffs may overlie Calico Hills tuffs with few or no fractures. The sparsity of continuous fracture pathways may have important implications for water flow in the unsaturated zone.

Another important attribute of the Calico Hills is that analyses of surface and borehole samples (Bish and Chipera 1986; Broxton et al. 1993) show an abundance of zeolite minerals in all units of the Calico Hills Formation. Zeolites are silicate minerals that have the ability to sorb (attach or bind) radionuclides and other ions that may be transported in solution in water. The process of sorption may significantly slow the movement of many radionuclides away from a repository. Carey et al. (1997) has constructed a three-dimensional model of mineral distributions at the Yucca Mountain site so that performance models can simulate the effects of sorbing minerals on flow and transport. A factor that complicates potential retardation analysis is that the formation of zeolitic minerals may reduce the porosity and permeability of the rock, so that the rock may not be able to accommodate the volume of water flowing into it. Additional discussion of the effects of zeolite alteration is presented in Section 2.2.5.

**Crater Flat Group.** The Crater Flat Group consists of three sequences of rhyolitic, moderate to large volume ash flow deposits and interlayered bedded tuffs. In descending order, these formations are the Prow Pass, Bullfrog, and Tram tuffs (Sawyer et al. 1994). The Bullfrog tuff is associated with the Silent Canyon caldera complex, but sources of the Prow Pass and Tram tuffs are less certain. The Crater Flat Group is distinguished from other units near Yucca Mountain by the relative abundance of quartz and biotite crystals. In addition, the Prow Pass tuff and, to a lesser degree, some parts of the Bullfrog tuff contain distinctive rock fragments of reddish-brown mudstone. At Yucca Mountain, the Crater Flat Group overlies dacitic (very fine crystalline or glassy rock) lavas and flow breccias (rocks composed of angular fragments of other rocks) in the northern part of Yucca Mountain, and the Lithic Ridge tuff in the southern part (Broxton et al. 1989).

The Prow Pass tuff is a sequence of variably welded ash flow deposits formed by eruptions from an unidentified source between about 13.0 and 13.2 million years ago (Sawyer et al. 1994), and ranging from about 84 to 198 m (275 to 650 ft) in thickness. Individual tuff units range from less than 1 m to approximately 80 m (3.3 to 263 ft) in thickness, and are commonly zeolite altered. Ash flows units can be distinguished by their pumice and lithic clast (rock fragment) content. Interlayered airfall deposits and breccia deposits are present locally. Alteration of the tuff matrix to zeolite and clay minerals is common, but vitric zones containing unaltered volcanic glass are present in some areas, most notably beneath the southwestern part of the repository block.

The Bullfrog tuff consists of welded to partially welded, zeolite altered upper and lower zones separated by a central zone of moderately to densely welded tuff with weathered bedded tuffaceous deposits at the base. The measured thickness of the entire sequence ranges from 89 m (292 ft) to as much as 400 m (1,312 ft) in southern Crater Flat.

The Tram tuff includes numerous units characterized by the variable abundance and types of pumice and rock fragments in ash flow deposits and rare bedded tuff interbeds. A lower lithic-rich unit (high rock fragment content), and an upper lithic-poor unit have been recognized. Welding is variable: in general, the lithic-poor unit is more densely welded than the underlying lithic-rich unit. Clay and zeolite alteration occurs in both units of the Tram tuff. The thickness of the Tram tuff ranges from about 182 to 381 m (597 to 1,250 ft).

**Faulting and Structural Geology.** The spatial and temporal distribution and properties of faults and fractures in the volcanic bedrock are fundamental elements of the structural geology of the potential underground repository at Yucca Mountain. They control the hydrologic and rock mechanical properties of the system, and, therefore, they may strongly affect both performance and design. In recognition of this fact, NRC considers the determination of viable models of fractures and site discontinuity features as a subissue under the Structural Deformation and Seismicity Key Technical Issue (NRC 1997a) (see Volume 4, Section 4.3.3.2). Documentation and discussion of fracture and fault patterns are based on detailed surface and underground geologic mapping conducted at detailed scales from 1:2,400 to 1:24,000. Faults with 5 or more meters of offset were recorded on the 1:24,000 mapping; faults with 1–5 m (3–16 ft) of displacement were mapped in the more detailed studies.

Figure 2-11 (Day et al. 1997) depicts the area informally called the Yucca Mountain site area. This is a 12 by 14-km (7 by 9-mile) region extending from the Prow on the north to Busted Butte on the south and from Windy Wash on the west to Fortymile Wash on the east. The structural geology of Yucca Mountain is controlled by block-bounding faults spaced 1–4 km (0.6–2.5 miles) apart. These faults include (from west to east) the Windy Wash, Fatigue Wash, Solitario Canyon, Bow Ridge, and Paintbrush Canyon faults. Dune Wash and Midway Valley faults are also block-bounding faults, but they differ from the other block-bounding faults in that they have no evidence of Quaternary movement (within the past 1.6 million years). The

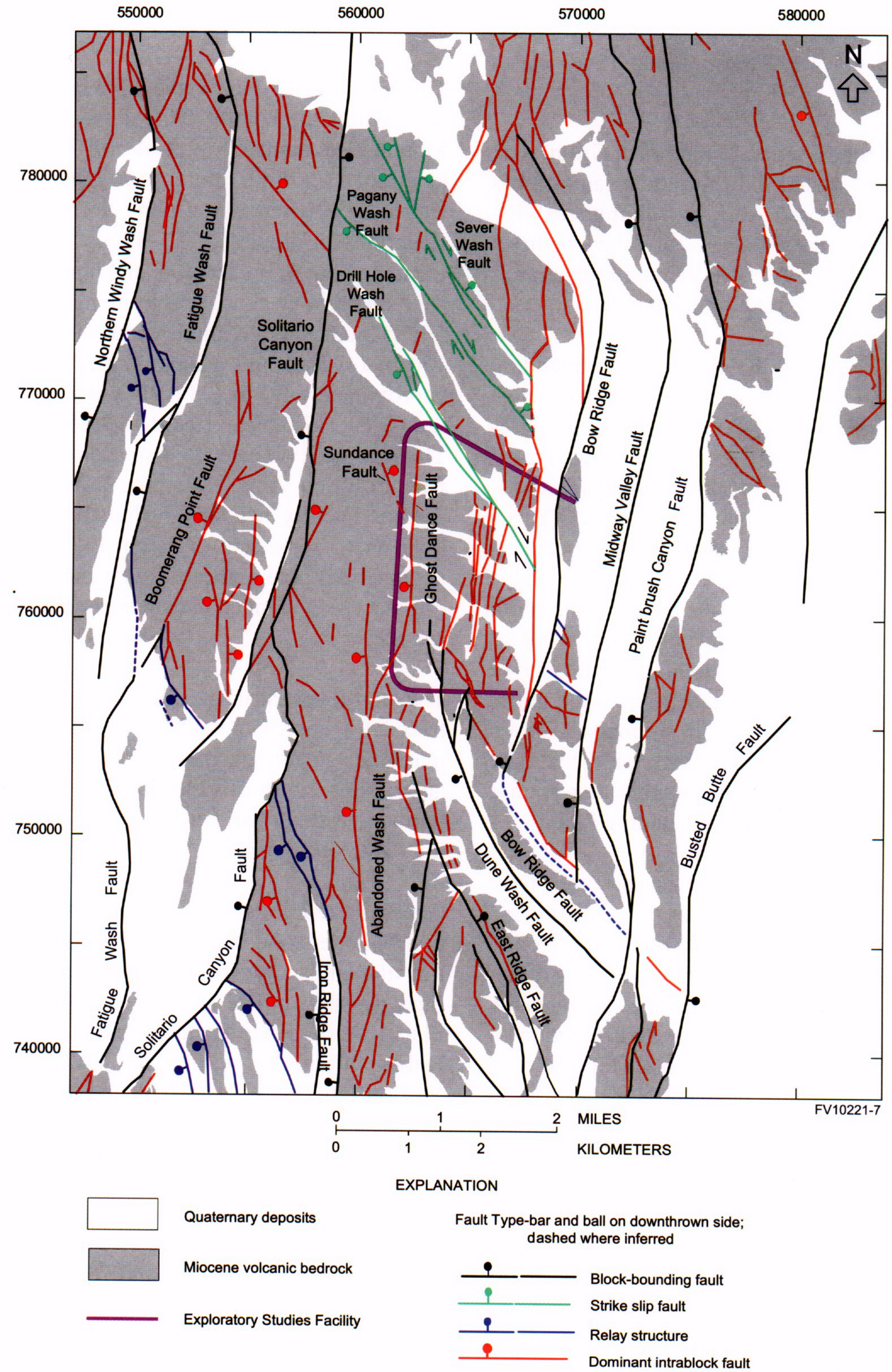


Figure 2-11. Faults in the Yucca Mountain Area
(Source: Day et al. 1998)

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block-bounding faults commonly dip 45°–85° to the west. Some left-lateral displacement is commonly associated with these faults (Day et al. 1997).

In some fault zones, several Paintbrush Group rock types have been mixed indicating that faulting has structurally juxtaposed various subunits as displacement and deformation of the bedrock occurred (Day et al. 1997). Individual fault strands within these zones are highly brecciated.

Displacement between the major block-bounding faults occurs along multiple smaller faults, which intersect block-bounding faults at oblique angles (Day et al. 1998). These "relay" faults are significant components of the block-bounding fault systems particularly in the southern half of Yucca Mountain. Most of the smaller faults occur in complex zones of faulting. Through most of the site area, block-bounding faults strike to the north and relay faults strike to the northwest, whereas south of the site area, block-bounding faults strike to the northeast and relay faults strike to the north. Within structural blocks, small amounts of strain are accommodated along intrablock faults that may represent local structural adjustments in response to displacements on the block-bounding faults.

Ten structural domains within the site area have been defined, each characterized by a distinctive structural style (CRWMS M&O 1998d, Section 3.6.2.3.2). The patterns that characterize individual domains may include the nature and intensity of faulting as well as magnitude and direction of bedrock dips. Most of the potential repository is within an area known as the Central Yucca Mountain domain. Structurally, this is the simplest and largest domain, comprising three east-tilted blocks, each 1–4 km (0.6–1.8 miles) wide, bounded by west-dipping block-bounding faults. Intrablock faults are locally present such as the north-striking Ghost Dance and Abandoned Wash faults in the Central Block, and the Boomerang Point fault in the Jet Ridge Block. These intrablock faults have a maximum of tens of meters of west-side-down displacement and tend to be associated with a simple, narrow zone of deformation in contrast to the hundreds of meters of displacement and complex deformation zones commonly associated with block-bounding faults.

The Ghost Dance fault is the main intrablock structure within the central part of the Central Yucca Mountain domain (Day et al. 1997) with a trace length of 3.7 km (2.3 miles). In general, the Ghost Dance fault is a north-striking normal fault zone, steeply west-dipping (75°–85°). The displacement, amount of brecciation, and number of associated splays vary considerably along its trace. The fault zone has a maximum width of approximately 150 m (492 ft) and a maximum displacement of approximately 30 m (98 ft) down-to-the-west offset (CRWMS M&O 1998d, Section 3.6.2.4.1.1). There is no evidence of displacement during the past 2 million years. Mapping in the Exploratory Studies Facility has shown that the Ghost Dance fault has a consistent dip from the surface to the depth of the potential repository, but that the zone of brecciation is much narrower at depth than at the surface.

The northwest-striking Sundance fault can be traced for approximately 750 m (2,460 ft). The maximum width of the Sundance fault zone is approximately 75 m (246 ft), and the cumulative northeast-side-down vertical displacement across the fault zone does not exceed 11 m (36 ft).

Geologic relations beneath Fortymile Wash are poorly understood because the bedrock geology of this domain is largely concealed by the Quaternary (and possibly older) surficial deposits of Jackass Flats. A fault has been postulated, east of Fran Ridge within the wash (CRWMS M&O 1998d, Section 3.6.2.3.2). The fault has no geophysical expression and no known Quaternary offset.

**Fracture Characteristics.** Fractured rock mass studies have included detailed studies of the distribution of fractures in natural exposures, cleared pavements, and underground excavations. The largest volume of fractured-rock-mass data comes from the detailed mapping of the Exploratory Studies Facility. Sweetkind and Williams-Stroud (1996) and Sweetkind, Barr et al. (1997) summarize the results of fracture studies. Fractures are generally of three types: early cooling joints, later tectonic joints, and joints due to erosional unloading. Cooling and tectonic joints have similar orientations, but cooling joints are smoother. Cooling joints form two orthogonal sets of steeply dipping fractures and, locally, a set of subhorizontal fractures. For tectonic joints, four steeply dipping sets and one subhorizontal set have been identified.

Fracture density, connectivity, and hydraulic conductivity may all strongly influence groundwater flow within the volcanic rocks. Because of their greater brittle strength, values for all of these fracture parameters are greatest in the densely welded tuffs and least in the nonwelded units. The Tiva Canyon welded and Topopah Spring welded units are characterized by well-connected fracture networks, whereas the Paintbrush nonwelded units and the Calico Hills tuffs generally do not exhibit connected fractures. Values are intermediate in the lithophysal zones of welded tuffs, because fracture propagation may be attenuated in the voids. In the Crater Flat tuffs, fracture density is variable, both vertically and laterally, due to the variations in tuff properties.

In addition to distributed fracture networks, one other important fracture-related parameter is the extent of alteration of hydraulic properties around fault zones, which may provide a fast flow pathway through hydrologic units that are otherwise not prone to fracture flow. Even non-welded units, such as the Pah Canyon and Calico Hills tuffs, may transmit significant water flow in fractured zones adjacent to faults. Based on observations in the Exploratory Studies Facility, the zone of influence around faults, in which fracture properties are modified, may range from approximately 1 to 7 m (3 to 23 ft) (Sweetkind, Barr et al. 1997). The extent of property modification does appear, in a general way, to correlate with the total fault displacement. The amount of deformation associated with the faults also depends on the lithology of the units involved in the faulting. Non- to partly-welded portions of the crystal-poor vitric zone of the Tiva Canyon tuff apparently can accommodate a greater amount of extensional strain before failing by fracture than can brittle, densely welded rocks.

**Integrated Site Model.** The stratigraphic and structural data from the site have been combined with rock property and mineralogical results to build an integrated site model (CRWMS M&O 1997e). Data from boreholes, surface geological mapping, and geophysical surveys form the basis for the conceptual understanding of the site's geologic framework. This framework has been used to develop spatial models of the distribution of geological, geotechnical, hydrological, mineralogical and geochemical parameters. The model thus supports the design of the potential repository, and provides the foundation for process models of how water moves through the mountain and how released radionuclides would be transported away from a repository.

The database for the site includes numerous measurements of physical properties of the rocks of the Paintbrush Group. Large-scale data include rock quality, hardness, and key block analysis from the Exploratory Studies Facility, and weathering characteristics from outcrop. Laboratory data include mineralogy (including minerals with possible health effects such as polymorphs [different mineral forms with the same chemical composition] of silica and erionite), as well as density and porosity. Laboratory data also include thermal conductivity and expansion, heat capacity, static and dynamic elastic constants (expressed as Young's modulus and Poisson's ratio), confined and unconfined compressive stress, tensile and shear strength, and rock mass properties of strength and elastic moduli.

Studies to understand the geologic framework of Yucca Mountain are mature. Future geologic work will document the geology exposed in new underground excavations, provide the geologic support needed to carry out other specific studies, and collect information needed to design a repository.

**Selection of the Repository Horizon.** The identification of a subsurface repository block was based on several factors, including the following:

- Thickness of overburden
- Extent and characteristics of the host rock
- Location of faults
- Location of groundwater

The repository must be sited at sufficient depth to protect waste from exposure to the environment. For this reason, a minimum overburden thickness of 200 m (656 ft) was specified to ensure adequate protection from surface events.

The repository must also be sited within a suitable host rock, which means that the repository horizon must be able to sustain excavation of stable openings that can be maintained at reasonable cost during repository operations and to contribute to isolating the waste after closure. Without undergoing any changes that could threaten the repository's ability to safely isolate waste for an extended period of time, the rock should be able to accommodate the heat that will be generated. Finally, the host rock should be of sufficient thickness and lateral extent to allow for the disposal of the planned quantities of waste while simultaneously providing flexibility in selecting the depth, configuration, and location of the underground facility.

Faults could impact repository performance by detrimentally affecting the stability of underground openings, or by acting as pathways for water flow that could decrease waste package lifetimes and eventually lead to radionuclide release. The proposed repository was sited in an area that is relatively free of faulting; the proposed disposal area is bounded on the west by the Solitario Canyon fault and on the east by the Ghost Dance fault.

One of the major goals of the repository safety strategy is to minimize the exposure of waste to water. Separation from the saturated zone below the water table is a key component to selecting a potential repository horizon, and this was a significant factor in conducting further studies at Yucca Mountain. Moreover, it is important that the potential repository be isolated not only from present groundwater, but also from future fluctuations of the groundwater table. As described in Section 2.2.4, geologic evidence indicates that the water table has not been more than 100–120 m (328–394 ft) higher than its present level over the past several hundred thousand years, even during much cooler and wetter climates. Even at these high levels, the water table would still be 100–200 m (328–656 ft) below the repository horizon.

Mansure and Ortiz (1984) defined a 2,200-acre area (and five potential expansion areas) beneath Yucca Crest and its eastern flank that are large enough and thick enough to host a repository. CRWMS M&O (1997f) used computer analysis of a geologic model of the site to further refine the volume available for repository siting.

The combination of criteria resulted in the selection of the middle to lower portion of the Topopah Spring welded tuff as the potential repository horizon. This section is strongly welded with variable fracture density and lithophysal content. Experience underground in the Exploratory Studies Facility (monitoring of excavation characteristics, rock-bolt loads, deformation of portal girders, and the strain magnitudes of steel sets) and design analyses indicate that stable openings can be constructed in the Topopah Spring. Also, the thermal and mechanical properties of the rock should enable it to accommodate the range of temperatures expected during repository construction (CRWMS M&O 1997g). The selected horizon is well below the mountain surface and well above the water table. Finally, the repository volume is located between major faults.

**Health-Related Mineral Issues.** Certain minerals known to present a potential risk to worker health are present in the volcanic rocks at Yucca Mountain. The risks are generally related to potential exposures caused by inhalation of airborne particulates (dust). Some of the minerals represent a hazard commonly associated with underground construction, whereas other mineral species are rare and less well known. To protect the health and safety of underground workers, the Yucca Mountain Site Characterization Project (YMP) will continue to use safe, modern, underground construction practices to minimize and mitigate any risks. For example, low dust levels and adequate ventilation will be maintained. In addition, YMP will provide worker education on mineral health hazards, as well as sample and monitor for hazardous minerals.

Several minerals present at Yucca Mountain have been listed by the World Health Organization as carcinogenic, or probably carcinogenic, to humans (International Agency for Research on Cancer 1997). These include quartz, cristobalite, tridymite, and opal-CT. Quartz, cristobalite, and tridymite are polymorphs of silica ($SiO_2$), and opal-CT is a noncrystalline form of silica. Quartz is one of the most abundant minerals in the earth's crust, and it is widely distributed at the surface and underground at Yucca Mountain. The other silica polymorphs (cristobalite and tridymite) are less abundant than quartz but are still common in volcanic tuffs. Epidemiological data suggest that silica minerals generally represent a significant risk only at high and prolonged exposures, and that concurrent exposures to other agents may actually determine risk. Consequently, the risk associated with these minerals at Yucca Mountain can generally be successfully mitigated by proper dust controls consistent with modern standard practice in underground construction.

Erionite is an uncommon zeolite mineral that was recognized by the International Agency for Research on Cancer as a human carcinogen in 1987; at Yucca Mountain, it is known to occur primarily in the basal vitrophyre of the Topopah Spring tuff and in isolated zones of the Tiva Canyon tuff. At low doses erionite is believed to be a potent carcinogen capable of causing mesothelioma, a form of lung cancer. As a result of its apparent carcinogenicity, erionite could pose a risk if encountered in quantity during underground construction even if standard modern construction practices are followed. Because erionite appears to be absent or rare within the proposed repository horizon, most repository operations should not be affected. However, precautions would be taken when penetrating horizons in which it may occur during construction, such as in the basal vitrophyre of the Topopah Spring unit.

A number of other minerals present at Yucca Mountain may have associated health risks if prolonged exposures occur; however, there is no evidence suggesting a link to cancer. Therefore, the International Agency for Research on Cancer (International Agency for Research on Cancer 1997) has ranked these substances not classifiable. Some of the minerals identified and considered in establishing health and safety practices for potential repository operations include the zeolite group minerals mordenite (which is fibrous and similar in some respects to erionite), clinoptilolite, heulandite, and phillipsite. Because there is no known risk associated with the other zeolite minerals, and because they are primarily found in nonwelded units below the repository horizon, it is unlikely that they represent a significant risk. The dust control measures implemented to mitigate risk from silica should also protect workers from exposure to other minerals.

Palygorskite, sepiolite, smectite, mica, kaolinite, feldspars, calcite, and manganese oxides have also been analyzed to determine whether they present any risk to underground workers. Some of these phases are rare (e.g., palygorskite, sepiolite, and manganese oxides occur predominantly in fractures), whereas others are common (especially feldspar). In all cases, standard practices for dust control would effectively minimize risks.

#### 2.2.1.3 Surficial Deposits and Processes

Surficial deposits in the Yucca Mountain region are important in understanding potential repository performance for two major reasons. First, they provide a record (albeit an incomplete one) of the evolution of surface processes and climate conditions over the past several hundred thousand years. Second, they are an important component of the hydrologic system. The distribution and characteristics of surficial deposits are important factors in determining the rate and extent of surface water infiltration into the mountain, and they are also one component of the valley-fill aquifer in some areas.

Most surficial deposits are composed of alluvium (coarse sand and gravel sediments deposited by flowing water), but hill slopes are typically covered with a thin veneer of colluvium (coarse sediments deposited by downhill creep). Eolian deposits (windblown deposits such as sand dunes) are generally a minor component of the surficial deposits except for a massive star dune at Big Dune and sand ramps such as those that flank Busted Butte. Southwest and south of Yucca Mountain minor spring and marsh deposits, reflecting past wetter climates, have been mapped and studied (Paces et al. 1996b). The ages of surficial deposits range from less than 1,000 years to greater than 760,000 years, but most deposits exposed at the surface were deposited during the last 100,000 years.

Average erosion rates have been estimated for colluvial deposits, hill slopes, bedrock ridges, and stream valleys (CRWMS M&O 1998d, Section 3.4.5). All evidence suggests that erosion in the Yucca Mountain region has generally proceeded slowly. Volcanic features are well preserved, and basic geologic relationships indicate that modern landforms (ridges and valleys) were already established by the time of the Rainier Mesa tuff eruption approximately 9.5 million years ago. The Rainier Mesa unit was deposited in valleys caused by faulting along the Solitario Canyon, Bow Ridge, Midway Valley and other major faults. Various techniques have been used to calculate erosion rates including studies of alluvial stratigraphy and erosion history in Fortymile Wash. Other techniques include dating boulders and cosmogenic exposure ages (the length of time a surface has been exposed to the sun) on hill slopes, and calculating the accumulation rate of latest Pleistocene alluvium in Midway Valley. These methods have yielded long-term erosion rate estimates from approximately 0.1 to 1.1 cm (0.04 to 0.43 in.) per thousand years. The higher estimates were for the generally wet period, from 27,000–2,000 years ago, and are believed to represent maximum expected erosion rates above the potential repository. The data suggest that significant erosion near the proposed repository was unlikely to have existed during the Quaternary and is unlikely under current climate conditions. No further work is planned.

Near-surface carbonate deposits (sometimes called caliche or calcrete), that occur in soils parallel to the surface and as fracture fillings, provide evidence of past surface hydrologic conditions. Available evidence indicates that the majority of carbonate deposits are pedogenic in origin (related to soil formation), indicating that past climate has been wetter than modern conditions (Stuckless et al. 1998). These types of deposit form in arid environments when downward infiltrating rainwater dissolves carbonate minerals present at the surface. The carbonates are precipitated again when the infiltrating water evaporates. The physical and paleontological (fossil) characteristics of the deposits are similar to pedogenic deposits observed throughout the southwestern United States, and they differ from those for spring deposits characterized by flowing water. Mineralogic data, analyses of major and trace element geochemistry, and stable isotope and radiogenic tracer isotope analyses also indicate the deposits have a close affinity to local soils. The geochemical data also indicate that the carbonates could not have been precipitated from any known groundwater near Yucca Mountain or at the temperatures of regional groundwater.

An alternative hypothesis for the origin of the carbonate deposits proposed that they were the result of groundwater upwelling caused by seismic pumping (Szymanski 1987; 1989). This model postulated that the water table could fluctuate hundreds of meters over short periods of time due to the stresses associated with seismic events. Because such large-scale water table excursions could potentially rise above the level of the proposed repository, this hypothesis could have significant implications for repository performance. Therefore, the project performed numerous studies to resolve the origin of the deposits, and requested a panel convened by the National Academy of Sciences National Research Council to review the results. The panel concurred with the project conclusion that none of the evidence cited by Szymanski for groundwater upwelling near Yucca Mountain could reasonably be attributed to that process. They also agreed that available evidence supported the view that the carbonates formed from meteoric water and surface processes (National Research Council 1992, p. 56). The panel also evaluated the theoretical basis for the model of upwelling water, and concluded that the proposed mechanism was inadequate to raise the water table more than a few tens of meters and that water table excursions to the design level of the repository would be unlikely.

More recently, Hill et al. (1995) examined the origin of the near-surface carbonate deposits. They cited new observations supporting an origin related to upwelling groundwater. Stuckless et al. (1998) reviewed their hypothesis and evidence and concluded that a pedogenic origin remains the preferred interpretation.

The Nuclear Waste Technical Review Board has also recently reconsidered the issue of possible future upwelling of water into the proposed repository. The Board concluded that the material they reviewed "does not make a credible case for the assertion that there has been ongoing, intermittent hydrothermal activity at Yucca mountain or that large earthquake-induced changes in the water table are likely at Yucca Mountain," (Nuclear Waste Technical Review Board 1998).

### 2.2.2 Climate and Weather

Climate and its changes over time directly affect system performance at Yucca Mountain. Precipitation and surface weather conditions limit the infiltration of water into and through the mountain.

Designing an engineered barrier system to limit contact between waste and water at Yucca Mountain depends on understanding the natural behavior of water at the site. While the Yucca Mountain climate is currently very dry and hot, past climate records show this was not always the case. Therefore, establishing credible future climate states is important because the future will likely be similar to past climates that have been wetter and cooler than today's.

Information from climate studies addresses several of NRC's key technical issues, most directly the issue of Unsaturated and Saturated Zone Flow Under Isothermal Conditions (NRC 1997a). In addition, results help to answer questions related to the issues of Total System Performance Assessment and Integration, and Activities Related to Development of the U.S. Environmental Protection Agency Yucca Mountain Standard. The NRC key technical issues are discussed in more detail in Volume 4, Section 4.3.3.

#### 2.2.2.1 Overview of Site Climate

The nature of climate over the next 10,000–100,000 or more years is an issue that must be addressed concerning the potential Yucca Mountain repository. Present-day climate is hot and dry. The rain shadow caused by the Sierra Nevada and other mountain ranges limits the number of storms capable of generating precipitation throughout the Great Basin. Near Yucca Mountain, precipitation comes from the rare winter intrusion of frontal storms associated with polar fronts and, during the summers, the regular intrusion of hot, dry, subtropical high-pressure weather systems. Local vegetation on all but the highest mountains is limited by the available water and typically uses most of the available precipitation. Therefore, infiltration into the underlying rock is modest and commonly associated with wet years that are linked to El Niño cycles.

Studies of past climates indicate that climate oscillates between glacial and interglacial periods. The current climate is generally typical of interglacial periods although paleoclimate records suggest that the present interglacial period is hotter and drier than earlier interglacial periods. In contrast to the current climate, periods of more extensive glaciation have dominated the long-term climate for most of the past 500,000 years. Glacial periods (also called pluvial periods), characterized by wetter and colder conditions than the present, have prevailed over approximately 80 percent of that time. The coldest and wettest glacial periods are termed superpluvials.

During glacial periods, frontal storm activity is common and related to the residence of the polar front far south of its modern average seasonal position. Summer intrusion of subtropical high-pressure systems is less frequent to nonexistent. Local vegetation is less water limited and average air temperatures are colder, leading to much lower evapotranspiration and higher infiltration than today. Mean annual precipitation shifts from substantial summer rain to winter precipitation, often as snow. Wetlands are common on the valley floors, and local streams are active during all or most of the year. Large closed basins, such as

Death Valley, contain lakes. Such climates are generally characteristic of glacial periods, but particular glacial periods vary. Some are relatively warm and wet; whereas, others are cold and may be either wet or dry.

Figure 2-12 depicts a range of climatic conditions that have existed at Yucca Mountain in the past, and could be present in the future. The figure shows schematically the current semiarid climate, a long-term average climate representative of typical glacial conditions over the past several hundred thousand years, and a superpluvial (superglacial) climate that simulates the coldest and wettest conditions likely to occur. Precipitation in these states ranges from approximately 170 mm (7 in.) per year in the present day to 300 mm (12 in.) per year as a long-term average, to 450 mm (18 in.) per year or more in superpluvial conditions. The cooler temperatures and decreased evapotranspiration also will cause a much higher fraction of precipitation becoming infiltration.

The timing for the initiation of glacial periods is related to the earth's orbit. The present interglacial period is nearing an end, and transition to a glacial period could begin in a few centuries or millennia. Earth's orbital parameters over the next 100,000 years most closely resemble features from 400,000 to 300,000 years ago. Study of long-term climatic records from the region suggests that the glacial period 400,000 to 300,000 years ago was a relatively warm, wet glacial period.

#### 2.2.2.2 Present-Day Climate and Weather

Present-day climate in southern Nevada is semiarid, with hot summers and mild winters. The regional weather is influenced by complex topography and weather system circulation patterns.

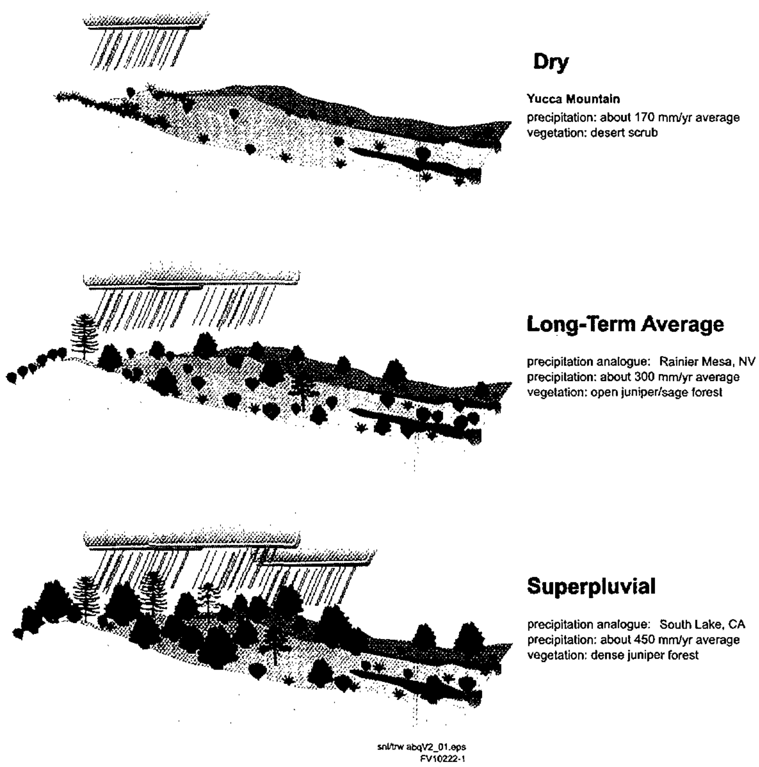


Figure 2-12. Conceptual Drawing of Projected Climates for Yucca Mountain

Local and regional monitoring stations provide weather data for the vicinity of Yucca Mountain. The annual average precipitation in the Yucca Mountain area is approximately 100–250 mm (4–10 in.) per year, depending on topographic elevation and exposure. About 30 years of monitoring at Amargosa Farms southwest of Yucca Mountain indicates an average of about 100 mm (4 in.) per year; at a station 10 km (6.2 mile) east of Yucca Mountain average precipitation is 133 mm (5.2 in.) per year; geostatistical studies suggest an average of 250 mm (10 in.) per year at higher elevations along the north of Yucca Mountain (CRWMS M&O 1998d, Sections 4.1.3.2 and 5.3.4.1.2.2). The estimated annual potential evapotranspiration (maximum surface moisture loss to the atmosphere) is 1,680 mm (66 in.) per year (Houghton et al. 1975). Snowfall is infrequent, light, and short-lived below about 1,070 m (3,510 ft) above mean sea level. The estimated maximum daily rainfall is bounded by a value of 125 mm (5 in.) (CRWMS M&O 1997a).

The annual average temperature in the Yucca Mountain area ranges from about 15 to 18°C (59 to 65°F), depending on elevation. Summer temperature can exceed 40°C (104°F), and winter temperatures occasionally fall below 0°C (32°F). Low relative humidity throughout most of the year is indicative of the semiarid climate; the annual average dew point temperature is about -5°C (23°F). Regional weather systems and the mountain and valley topography cause a regular wind pattern of well-mixed airflow toward the north during the daytime and stable (low mixing) airflow toward the south into Amargosa Valley at night.

The aridity and warm temperatures result from a combination of large-scale atmospheric circulation patterns and the large mountain ranges, such as the Sierra Nevada, on the moisture pathway from the primary source, the Pacific Ocean. The Yucca Mountain area is affected by typical mid-latitude global circulation patterns, with weather systems moving from west to east. Storms moving into the area from the southwest during winter tend to have the greatest potential for high precipitation as rain or snow. Significant late summer, southwest monsoon precipitation events occur with moist airflow from the south originating either in the Gulf of Mexico or the Pacific Ocean. Naturally recurring short-term changes in typical circulation patterns alter storm paths and precipitation patterns. One example is the El Niño pattern, which tends to increase winter precipitation in Southern Nevada by approximately 50 percent.

#### 2.2.2.3 Paleoclimate

Past climate history offers a basis to examine the factors responsible for climate change. Interpretation of paleoclimate records also provides a rationale to link elements of the hydrologic system (e.g., infiltration, movement of water through the unsaturated zone, elevation of the regional water table, groundwater discharge) with the climate history that drives them. Although projecting future climate involves many uncertainties, future climate variability will likely fall within the bounds of past climate variability. In addition, if the factors responsible for climate change are well understood, projections of climate over the next 100,000 years may be constrained to be similar to a particular period in the past.

**Global Climate Change.** Evidence of the earth's climate for the past 500,000 years shows oscillations between interglacial and glacial periods. Interglacial periods are those ages in recent earth history when continental ice sheets have been small. On a global scale, interglacial periods are warm periods; regions around 30° north or south latitude fall within hot-desert belts that result from global-scale atmospheric circulation features. Today, the earth is experiencing an interglacial period, and Yucca Mountain is on the northern edge of the hot-desert belt. During glacial periods, large continental ice sheets have extended well into the United States and central Europe. Near Yucca Mountain, glacial periods are typically wetter and cooler than the current climate.

Evidence of the cyclic nature of climate comes from long-term climate records. Long-term climate records, those that are tens of thousands to a million or more years long, are derived principally from sedimentary records in the world's oceans, the thick ice caps in Greenland and Antarctica, and sedimentary records in some lakes. Oceans contain long records (millions of years) of global climate change preserved in marine sediments. Ongoing scientific studies indicate that microfossils and stable isotopes from these sediments vary in response to climate change and act as proxies or substitutes for direct observation of past climates. Similarly, ice cores taken from the ice caps of Greenland and Antarctica provide high-resolution records of changes in the isotope values of precipitation caused by change in the earth's cycle. Those isotope values change in a systematic way with the coming and going of glacial climates.

Just as the earth has been characterized by different climates in its past, similar climates will likely characterize its future. The timing of climate change from the interglacial through glacial periods is believed to correlate to well-known, cyclic changes in the earth's orbit. These changes affect the amount of solar radiation (known as insolation) the earth receives. Interpretation of data from long-term climate records shows cyclical change in the global environment that seems to appear and disappear in tandem with the orbital cycles. During the last 500,000 years, interglacial periods have existed approximately 20 percent of the time and glacial periods have existed the remaining 80 percent of the time (Winograd et al. 1997). The transition from the present interglacial period into the next glacial period could begin in the next few hundred or thousands of years (Forester et al. 1996).

**Climate Change in the Yucca Mountain Region: Long-Term Climatic Records.** Scientists have established a relation between global climate change and long-term climate change in the Yucca Mountain region. Three long-climate records (locations of which are shown on Figure 2-13) occur within 100 miles of Yucca Mountain: Devils Hole, Owens Lake, and Death Valley. Devils Hole (about 50 km, or 31 miles, southeast of Yucca Mountain), yields a well-dated, stable isotope record from calcite that was deposited on the submerged walls of a fissure within the regional carbonate aquifer. Owens Lake contains a long record of lake sediments containing fossil and stable isotope evidence of climate change. That evidence may be interpreted in terms of precipitation and runoff from the Sierra Nevada and ultimately in terms of general changes in atmospheric circulation. Lake and stream sediments from Death Valley, California provide a record of lake conditions and stream flow into the valley, including flow from the Amargosa River and other drainages near Yucca Mountain.

The Devils Hole record, with its extensive and accurate chronology, establishes the timing and duration of climate change in the Yucca Mountain region. The record also provides a means to compare climate change at Yucca Mountain with records throughout the world. Figure 2-14 shows the correlation between climate-sensitive oxygen isotope records from Devils Hole and the globally averaged marine isotope record known as SPECMAP (Spectral Mapping Project) (Winograd et al. 1992; Imbrie et al. 1984).

Owens Lake, a present-day playa (the dry flat bottom of an undrained desert basin) in Inyo County, California, approximately 160 km (100 miles) west of Yucca Mountain (see Figure 2-13) contains a thick sequence of lake sediments. Cores of those sediments span the past 800,000 years. Interpretation of the Owens Lake climate record (Smith and Bischoff 1997) provides information about the magnitude of change in precipitation and air temperature during past climate periods and, therefore, complements the Devils Hole record. Over the past 500,000 years, Owens Lake has been fresh (implying climates wetter than today) for approximately 80 percent of the time and saline (implying climates like today's) 20 percent of the time.

The Owens Lake record indicates changes from interglacial to glacial periods can occur rapidly, on a scale of a few centuries to two millennia (2,000 years). Such rapid changes from warm and dry to cold and wet climates indicate a southerly shift in the average position of the polar front and strengthening of westerly atmospheric flow. Further, the persistence of cool, wet climates implies that present-day hot, dry summers did not exist during glacial periods. The absence of hot, dry summers implies that the polar front, which today retreats into Canada, remained in the region year round. This indicates that intrusion of subtropical air did not occur during the summer for glacial periods.

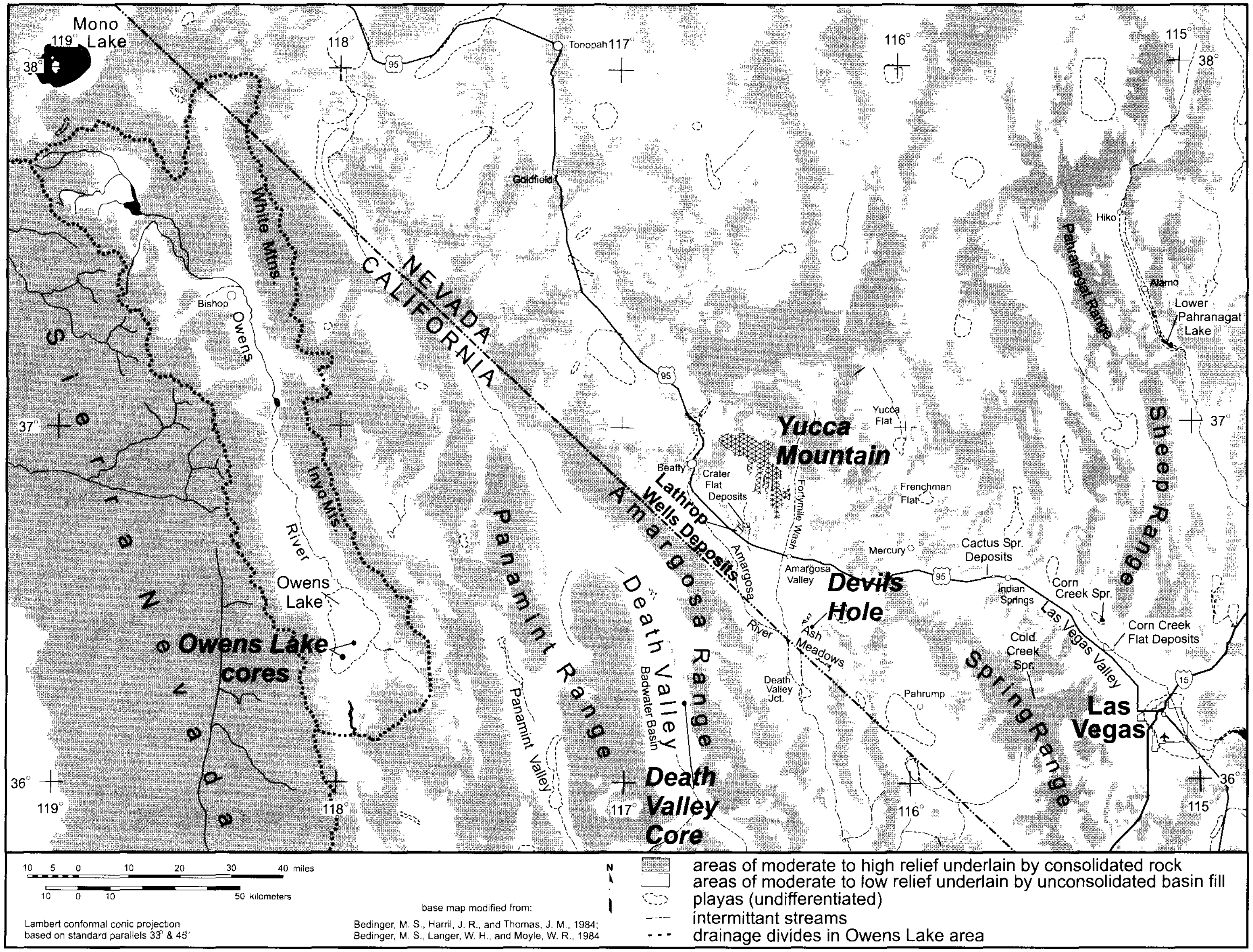


Figure 2-13. Geomorphology of the Southern Great Basin Showing Locations of Long-Term Climatic Records Near Yucca Mountain

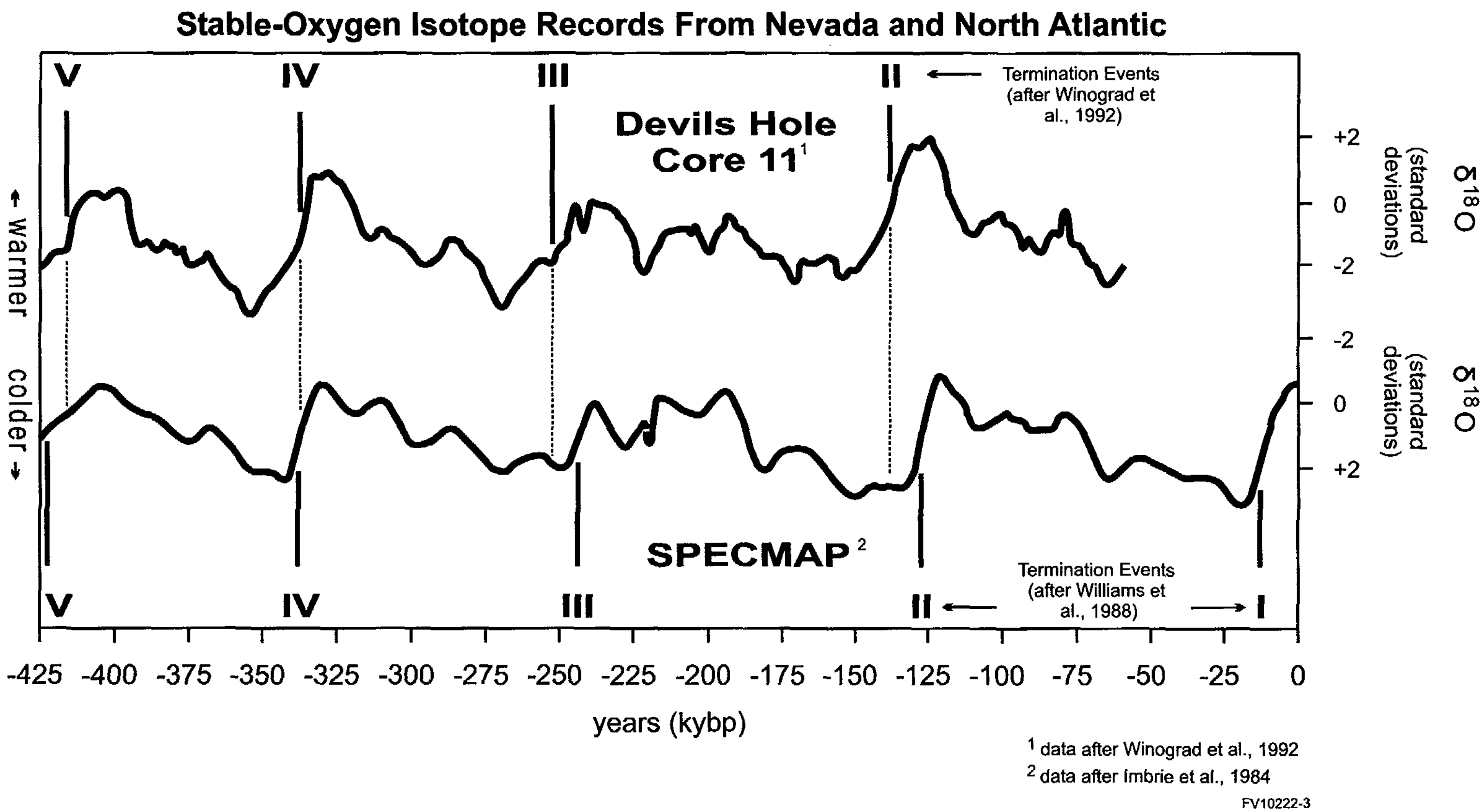


Figure 2-14. Stable-Oxygen Isotope Records From Nevada and North Atlantic

In addition to providing information on how climate differs between glacial and interglacial periods, the Owens Lake climate record also provides information on the variation among different glacial periods and among different interglacial periods. Some glacial periods, for example, are long, wet and very cold; others are wet and relatively warm and show significant climate variability within the period. Although extreme glacial climate exhibits exceptionally cold and wet conditions, other glacial periods differ significantly from it.

Sediments within Death Valley also reflect changes in climate for the Yucca Mountain region. Today, water on the Death Valley floor largely comes from spring discharge. Salt mineral deposition is common and related to the intense evaporation of the spring water. However, data from a 185-m (607-ft) sedimentary core, spanning a time period of about 200,000 years, show that during a previous glacial period a large, deep (90 m [295 ft] or deeper), and relatively freshwater lake filled Death Valley (Li et al. 1995). Lakes in Death Valley were potentially fed by three major sources of water: the Sierra Nevada via the Owens River, the Mojave River flowing from the Transverse Ranges in west-central California, or the Amargosa River draining the highlands north of Yucca Mountain. The persistence of lakes during cooler and wetter climate periods illustrates that effective moisture levels were much higher during glacial periods.

**Climate Change in the Yucca Mountain Region: Short-Term Climatic Records.** A number of important short-climate records exist within the Yucca Mountain area. They include pack rat middens, paleo-wetland and paleo-spring deposits (containing both sediments and fossils), and tree rings. These records document how past climates have affected the Yucca Mountain region during about the last 50,000 years.

Pack rat middens are deposits of fossil plant remains (e.g., twigs, leaves, pine needles, seeds, fruit, and pollen) and other material (including fecal pellets, bones and rocks) cemented by crystallized urine. Analysis of the middens provides information on climate conditions over time, because the plants available to the rats are indicative of existing conditions and because the plants and other organic matter can be dated by radiocarbon techniques (CRWMS M&O 1998d, Section 4.2.4.1). Studies of middens in the Yucca Mountain area reveal that Utah juniper, limber pine, and white fir were common trees during the period from approximately 35,000 to 12,000 years ago, indicating that conditions during the last glacial period were cooler and wetter than today (Spaulding 1990). Plants that typify the present hot, dry desert environment (e.g., creosote) were absent from the glacial landscape (Spaulding 1990) and did not become common until the late Holocene, approximately 4,000 years ago. These findings suggest the most recent glacial climate near Yucca Mountain was similar to that seen today in areas of northern Nevada where the current climate is colder and wetter. With montane conifers at lower elevations, the glacial climate probably had snowy winters and cool, dry summers.

Sedimentary deposits found on valley floors throughout southern Nevada show that during the last glacial period there were wetlands, flowing springs, and streams at low elevation (e.g., Quade et al. 1995). Emergent aquatic vegetation such as bullrush was common on the alluvial fan deposits sloping down from adjacent mountains and in the wetlands. The springs and wetland sediments contain fossils of numerous aquatic invertebrates. Those sediments, plus cave deposits, also contain vertebrate fossils including mammoths, timber wolves, pikas, northern pocket gophers, and northern meadow mice. Water birds such as ducks and wading birds also lived in the area during the late Pleistocene. The existence of wetlands throughout the region, together with the types of fossils found, provide further evidence that recent glacial periods were colder and wetter than today.

Interpretation of data from a paleodischarge (spring) deposit about 15 km (9.3 miles) southwest of Yucca Mountain (the Lathrop Wells Diatomite deposits, Figure 2-13) suggests that during glacial periods the regional water table was at the surface at this site (Paces et al. 1996b). Today, the regional water table at this location is approximately 100 m (328 ft) below ground surface. Whether the water table was as deep during previous interglacial periods is unknown. Thus, the magnitude of the climate effect on the level of the water table at this site is uncertain. At Devils Hole, the current low elevation of the water table appears to have developed only during the last 20,000 years (Szabo et al. 1994).

**Climate Change in the Yucca Mountain Region: Site Records of Climate Change.** Stable carbon and oxygen isotope values of calcite, that precipitated in fractures within Yucca Mountain, provide potential climate information related to infiltration. Carbon isotope data from calcite in the unsaturated zone exhibit values similar to those found in soil carbonates on or near Yucca Mountain. Quade and Cerling (1990) concluded that the carbonate in pedogenic calcrete filling the Bow Ridge fault and exposed in the near surface at Trench 14, which is located approximately where the Exploratory Studies Facility crosses the Bow Ridge fault (see Figure 2-11), formed during climates that were colder and wetter than the present. The authors correlated these carbon isotope values to those of modern soil carbonate forming at elevations of 1,800–2,000 m (5,906–6,562 ft), which is comparable in today's climate to the flanks of Rainier Mesa. Whelan et al. (1994) found that the oxygen isotopic values for past infiltration were variable within the range expected for precipitation.

#### 2.2.2.4 Future Climate

For performance assessment, the key challenge is to estimate the probable characteristics of climate in the future. Estimates of future climate may be obtained using two different methods. The first method predicts future climate from numeric models that use the equations of atmospheric physics together with climatic and oceanographic boundary conditions. The second method bounds future climate by identifying past climate cycles and forecasting future climate based on the present position within the cycle. Both methods have been used.

To predict future climate from models, four climate simulations were generated with the regional-scale model: present-day climate, full glacial climate (21,000 years ago), greenhouse effect scenario with double the current amount of carbon dioxide in the atmosphere, and greenhouse effect scenario with six times the current amount of carbon dioxide in the atmosphere.

The full-glacial state provides input for hydrologic models and is used to evaluate the output of the climate model for a nonmodern climate using climate proxies. The two greenhouse effect scenarios provide insight into human-induced climate change related to high levels of carbon dioxide in the atmosphere (Schelling and Thompson 1997). The model output suggests that increased carbon dioxide levels in the atmosphere could result in an increase in precipitation within the Yucca Mountain region.

Forecasting future climate depends on the assumption that climate is related to measurable and predictable processes, such as the variation in solar insolation caused by changes in earth orbit. Comparative analysis of the insolation and climate data over the past 400,000 years suggests a good correspondence between glacial/climatic and orbital cycles and provides a basis for future forecasts (CRWMS M&O 1998d, Section 4.3.2). Projections of future orbital characteristics and insolation profiles suggest that the next 100,000 years may be similar to the period from 400,000–300,000 years ago. Interpretation of climate proxy data from that period suggest that this period is characterized by a relatively short, warm, wet glacial period that was milder than some subsequent periods. Furthermore, past climate estimates provide information about the rates of change, duration, and magnitude of past precipitation and temperature to support hydrologic models.

For the VA performance modeling (described in Volume 3) the results of regional climate models were simplified to the three climate states depicted in Figure 2-12:

- Present-day climate, characterized by hot, dry conditions and low infiltration
- "Long term average" climate, presenting conditions typical of glacial periods, with much higher precipitation and infiltration rates

- "Superpluvial glacial" climate, representing the wettest, coldest conditions present over the past several hundred thousand years and characterized by very high precipitation and infiltration

#### 2.2.2.5 Status of Climate and Weather Studies

Through their studies at Yucca Mountain and its surrounding region, scientists have established the range of past climates that have affected the site. An understanding of the factors associated with climate change allows future climates at Yucca Mountain to be bounded. These results address the NRC subissue on the likely range of future climates at Yucca Mountain associated with the Key Technical Issue on Unsaturated and Saturated Flow Under Isothermal Conditions (NRC 1997a) (see Volume 4, Section 4.3.3.9). Further studies of past and future climates are not planned. Meterological conditions will continue to be monitored to confirm values used in assessing the performance of the site and to support preclosure safety operations.

### 2.2.3 Water Above the Water Table (Unsaturated Zone Hydrology)

The semiarid environment at Yucca Mountain is a fundamental attribute creating, in conjunction with topography, a hydrologic setting characterized by a very thick unsaturated zone. From the crest of Yucca Mountain, the water table is more than 2,000 ft (610 m) below the surface and approximately 1,000 ft (305 m) below the design repository horizon. Because the principal mechanism for radionuclide migration from the site is through solution and transport in groundwater, the thick unsaturated zone is a primary barrier in the repository containment system. This zone would limit the amount of water available to contact waste packages. If radionuclides are released from a waste package, the repository safety strategy would also rely on the natural system to delay and reduce the concentration of radionuclides during transport. Understanding the hydrology of the site (i.e., the flow of water within and away from the site) is key to assessing how well the proposed repository would perform.

Repository design is also intended to take advantage of the unsaturated nature of the site. Because of the relatively low volumes of water present in and flowing through the host rock, it is possible to design the local environment to reduce the amount of water contacting the waste packages. In addition, the design will also capitalize on the "free draining" nature of the welded tuffs to encourage water in fractures to flow through and past the repository horizon, rather than accumulating in drifts near the waste.

Figure 2-15 is a schematic drawing depicting the relationship of the major components of the hydrologic system from the surface to the water table. The remainder of this section describes the hydrologic setting of the site, including a conceptual description of the characteristics and processes that are most important to repository design and performance. The discussion follows the flow of water, starting with precipitation at the surface, infiltration into bedrock, flow through the unsaturated zone, and flow away from the repository into the saturated zone (see Section 2.2.4). Also presented are brief descriptions of the three-dimensional numerical models of unsaturated and saturated flow that have been developed for the site, key supporting data that provide insights about site conditions, and important processes that may affect repository performance.

An understanding of unsaturated zone hydrology is needed to answer questions related to NRC's key technical issues. Results presented in this section primarily address the issue of Unsaturated and Saturated Flow Under Isothermal Conditions (NRC 1997a). The results also address the issue of Total System Performance Assessment and Integration (NRC 1997a). These issues are described in more detail in Volume 4, Section 4.3.3.

#### 2.2.3.1 Surface Water Flow

Surface water flow at Yucca Mountain is important to repository design and performance for two reasons. First, the postclosure performance of the repository is a function of the volume and distribution of water flowing through the unsaturated zone, which in turn is limited by the water available at the surface. Second, surface facility design must

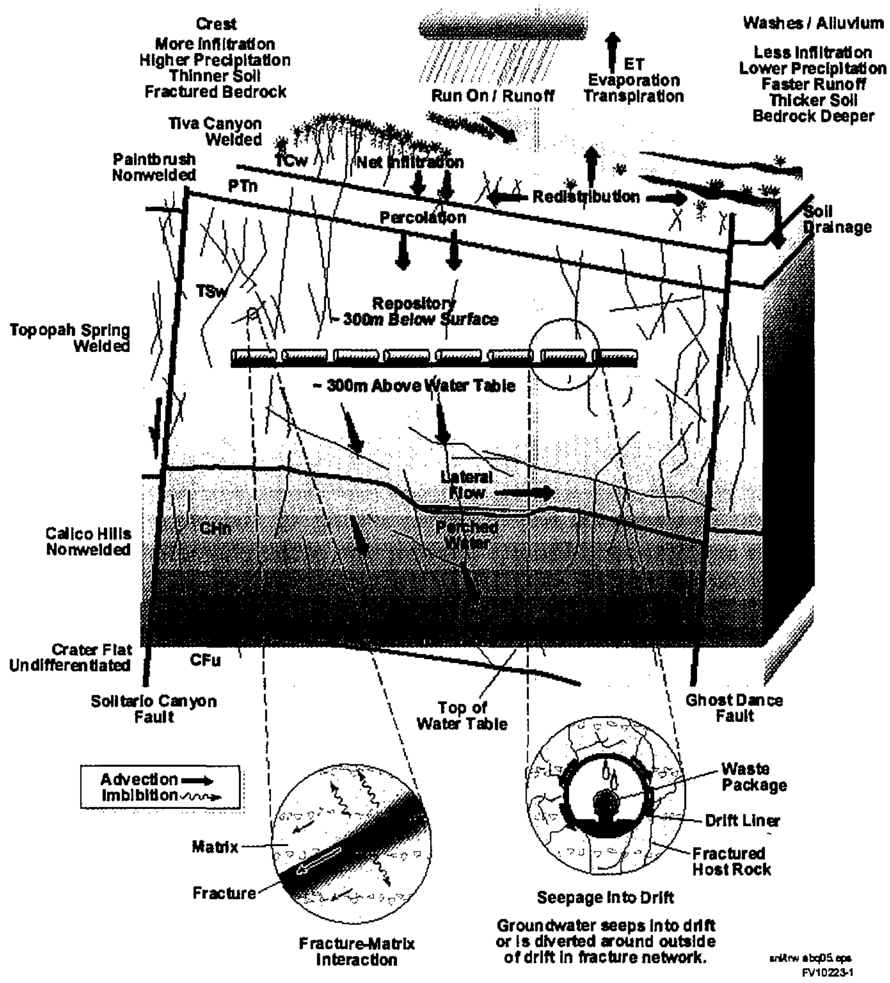


Figure 2-15. Conceptual Drawing of Unsaturated Zone Flow Processes

consider surface water flow (and flood potential) to ensure that storm events do not affect safe operation of the repository during the preclosure period.

As shown on Figure 2-15, surface water flow and infiltration are directly related to the climate, which controls the amounts and timing of precipitation, runoff, evaporation, and plant transpiration (uptake of water through the root systems). In hot dry climates like the present-day climate, summer precipitation is primarily from intense but localized thunderstorms that do not cause significant infiltration. Most of the water from such storms is lost to evaporation or transpiration within a week, unless an intense storm produces sustained runoff or subsequent storms provide additional water for deeper penetration. Thunderstorms can be so localized that runoff may occur in one wash and not in adjacent drainages. In contrast, winter precipitation occurring as snow or rain results primarily from Pacific frontal systems that tend to be more sustained and widespread than summer storms. These sustained but less intense storms may cause runoff after many hours or days of precipitation over a broad area. Also, slowly melting snow can penetrate more deeply into the subsurface because of lower winter evapotranspiration rates.

Presently, there are no permanent streams or other surface water bodies near Yucca Mountain or in most of the southern Great Basin. Springs sustain year round flow for short distances near Beatty in

Oasis Valley, about 25 km (15 miles) west of the site, and also about 100 km (62 miles) to the southwest in Death Valley. The steep western slope of the Yucca Mountain site drains to Solitario Canyon, which joins other channels that drain southward to the Amargosa River channel. Fortymile Wash, which drains southward from Pahute Mesa between Timber Mountain and Shoshone Mountain to Jackass Flats, collects runoff from several washes that drain the gentler, eastern slope of the potential repository site. Fortymile Wash also continues southward into the Amargosa Desert where it joins the Amargosa River.

Although flow in these channels is rare, the area is subject to flash flooding from intense summer thunderstorms or occasional sustained winter precipitation. In July 1984, for example, a peak discharge of 1,430 $ft^3$ (40.5 $m^3$) per second was measured in Fortymile Wash near Amargosa Valley just south of Yucca Mountain (Pabst et al. 1993). A peak discharge of 1,200 $ft^3$ (34.0 $m^3$) per second was measured at the same site in March 1995 (CRWMS M&O 1998d, Table 5.1-2, Map Designation number 38) and a lesser amount was estimated in February 1998.

Bullard (1986) developed probable maximum flood discharge hydrographs (water flow measurements) for the small basins of interest at Yucca Mountain. Blanton (1992) developed water-surface profiles for probable maximum flood discharges in the operations area. The topography and predicted extent of flooding have been used to design the operations area to limit flooding effects to temporary interruptions of operations.

### 2.2.3.2 Site Unsaturated Zone

The unsaturated zone at the Yucca Mountain site is as much as 750 m (2,460 ft) thick (Flint 1998, p. 7). The rock units that comprise the unsaturated zone include Quaternary surface deposits (alluvium and colluvium) and the Tertiary volcanic tuff section described in Section 2.2.1. As shown on Figure 2-15, the six principal hydrogeologic units that have been defined at the site include unconsolidated alluvium, Tiva Canyon welded, Paintbrush nonwelded, Topopah Springs welded, Calico Hills nonwelded, and Crater Flat tuff (Montazer and Wilson 1984, Table 1). Because of the importance of the unsaturated zone to performance, most site characterization activities performed over the past 16 years have focused on the properties and processes that define current site conditions, and on how the site would respond to the construction of a repository. This section presents site characterization results, beginning with an overview of the flow system, followed by a brief summary of the investigation results. The section concludes with a description of the detailed hydrologic model that has been developed to simulate flow and support site performance models.

**Overview of the Unsaturated Zone Flow System.** Figure 2-15 depicts schematically the key characteristics and processes that affect flow. Water flux through Yucca Mountain is limited by the rate of infiltration (flow from the surface into the mountain), which is a function of the amounts of precipitation, runoff, evaporation and transpiration (plant uptake). The rate at which these processes proceed is directly related to the distribution and characteristics of surface soils and rock at the site. Deep soils inhibit infiltration by allowing evaporation and transpiration to remove water; therefore, most infiltration probably occurs in areas with little soil cover. Estimating infiltration rates is difficult in semiarid environments, which are characterized by low total fluxes that may occur in rapid episodic events. An infiltration model under present climate conditions for the 43 $km^2$ (17 $mile^2$) area of the unsaturated zone model yields an estimated average infiltration rate of 4.9 mm (0.20 in.) per year. The average varies spatially from 0.0 mm (0 in.) per year in some washes to 40 mm (1.6 in.) per year toward the northern end of Yucca Mountain. For possible future climate conditions, model results indicate that the average annual net infiltration may increase by a multiple of 7-20. Because of the sensitivity of repository performance assessments to infiltration rates, a substantial effort has been undertaken to understand the variability and uncertainty inherent in the estimates.

The extent to which water is available to dissolve and transport waste is a function of the rates and distribution of water percolation (flow through the mountain). As shown on Figure 2-15, evidence indicates that surface infiltration generally moves downward rapidly in fractures through the Tiva Canyon tuff until it encounters the non-welded Paintbrush tuff. Flow in the non-welded unit appears to be predominantly in the rock matrix, although fast flow paths along faults, fractures, and other high permeability zones are present locally. In general, it appears that the Paintbrush non-welded unit attenuates (slows) and distributes flow downward, perhaps for periods of up to thousands of years. After migrating through the Paintbrush tuff, water moves into the welded Topopah Spring tuff, where flow again appears to be dominantly in the fractures. The distribution of flow is heterogeneous; in some areas characterized by widely dispersed or poorly connected fracture systems, percolation fluxes may be very low. In areas with highly transmissive features such as faults or dense fracture networks, significant volumes of water may move downward rapidly. Because percolation flux is important to repository performance, but inherently difficult to characterize in a semiarid environment, Yucca Mountain Site Characterization Project (YMP) has used numerous testing techniques in both surface-based boreholes and the Exploratory Studies Facility. These methods include measuring rock hydrologic and geochemical properties, monitoring ambient conditions in the unsaturated zone, studying fluid chemistry to assess their flow history, and analyzing the response of the system to the injection of fluids (both gas and liquid). Estimates of average percolation flux from these various studies range from about 0.1–18 mm (0.004–0.7 in.) per year. Because of Paintbrush tuff attenuation, most of the flux probably requires hundreds or thousands of years to reach the repository horizon. However, isotopic (chlorine-36) data suggest that at least a fraction of the flux reaches the repository level in tens of years or less. Thus, while some of the water moves downward quickly, much of it travels more slowly.

Seepage into the potential repository depends on the rate and distribution of percolation flux. Therefore, YMP has investigated the spatial distribution of percolation so that repository design and performance calculations can be based on a credible analysis of the likely range of conditions that would prevail after a repository was constructed and closed.

Below the repository, water will continue to flow primarily in fractures to at least the basal vitrophyre of the Topopah Spring, and then into the Calico Hills nonwelded unit (Figure 2-15). For performance assessments, it is important to understand the pathways and rate of flow of any water that may have contacted waste. Several characteristics of the underlying rock units and hydrologic conditions at the site are especially relevant to this analysis.

The existence of perched water zones (saturated zones with liquid water above other unsaturated rocks) below the repository horizon may cause water (and radionuclides) to move laterally, providing a flow path that bypasses the lower part of the unsaturated zone. Based on field studies and modeling, the occurrence of perched water at or above the repository horizon is believed to be unlikely. However, as shown on Figure 2-15, perched water zones are believed to be common at the contact of the Topopah Spring basal vitrophyre or at the vitric-zeolitic boundary in the Calico Hills unit beneath the repository. Because of the eastward dip of the hydrogeologic units, lateral flow in perched water zones could bypass lower portions of the unsaturated zone.

It is also important to understand the nature of flow of water through the Calico Hills and lower units which may vary spatially. Zeolite minerals present in the Calico Hills have the potential to retard (slow) the transport of radionuclides by absorbing them onto mineral surfaces. However, the effectiveness of sorption processes depends on interaction between flowing water and the rock matrix, and water in fractures may not interact significantly with the matrix. Under most of the proposed repository, the Calico Hills unit contains few fractures, and flow appears to be matrix dominated. However, in zones with abundant zeolites, low matrix permeabilities may be unable to sustain flux rates of more than a few millimeters per year. In these areas, any higher future fluxes would either cause perching and diversion, or would occur as fracture flow, which would result in reduced zeolite contact. Also, in the southern part of the potential repository, a significant portion of the Calico Hills unit is vitric (glassy, not zeolite altered) with relatively high fracture density. Here, sorption may not be effective, and flow through fractures could reduce the effectiveness of the Calico Hills as a barrier to radionuclide release.

In addition to understanding hydrologic processes, there are many other types of information that may be useful to understanding current conditions, and assessing the future behavior of the proposed repository. For example, studying the ages of the water present, and studying minerals deposited by water in the past, can provide insight into how the system has responded to past events. Similarly, studying the chemical composition of both water and rocks can help interpret the history and evolution of the site. All of the information collected will be used to assess how the Yucca Mountain site would respond to construction of a repository.

A numerical model of flow through the unsaturated zone incorporates information on the geologic framework and rock hydrologic properties. The model is calibrated using saturation and water potential data, gas pressures and flow rates, ambient temperature and heat flow data, locations and hydrochemistry of perched water bodies, and environmental isotope concentrations and water ages. The model yields a current range of estimated percolation flux at the repository horizon of approximately 1–20 mm (0.04–0.8 in.) per year.

**Results of the Unsaturated Zone Test Program.** The following sections describe key results from studying the Yucca Mountain unsaturated zone. These investigations have included testing rock properties in the laboratory and in situ (in the field), on the surface, in boreholes, and in the Exploratory Studies Facility. The tests measure properties at scales ranging from borehole core samples to mountain-scale monitoring of gas flow. The geochemistry of fluids in the unsaturated zone has also been analyzed to assess the evolution of the fluid chemistry which is a function of fluid flow history.

**Net Infiltration.** Estimates of net infiltration at the site under present-day and possible future climatic conditions are used to define the upper boundary condition of unsaturated zone flow models. They are then used to evaluate the performance of the potential repository (Flint et al. 1996). Data and interpretations from field studies at Yucca Mountain, combined with insights from the scientific literature, have led to a detailed understanding of the processes and properties that control net infiltration.

The processes include precipitation, surface runoff and overland flow, infiltration, evapotranspiration, and the redistribution of moisture in the shallow subsurface (Flint et al. 1996). Precipitation, which is the dominant hydrologic process at the site, depends mostly on meteorological factors, but also is affected by geographic location, elevation, and physiography. Evapotranspiration is the second most dominant hydrologic process and depends on vegetation, the distribution of moisture stored in the shallow subsurface, soil thickness, and the heat energy balance between the shallow subsurface and the atmosphere. Redistribution of moisture, combined with evapotranspiration, occurs in response to gravity and matrix potentials and depends strongly on soil and bedrock properties. Because all these physical processes are involved, net infiltration is both temporally and spatially variable, and it is a function of topography, physiography, storage capacity, vegetation, soil permeability and bedrock permeability. Infiltration tends to be highest in areas with relatively thin soil cover where other processes do not remove water (Flint and Flint 1995).

Moisture profiles have been measured over 11 years in 99 boreholes distributed over a large area of Yucca Mountain. Comparatively deep penetration of infiltration pulses occurs on ridge tops where soil is thin and bedrock is moderately to densely welded and fractured, even though the volumes of infiltrating water may be small. Most infiltration on ridge tops occurs during the winter. This is because lower-intensity storms have little or no runoff, and slowly melting snow results in slow but steady infiltration over a period of several weeks. Because of low storage capacity and exposed fractures, small volumes of water can infiltrate to significant depths on side slopes, especially on north-facing slopes where evapotranspiration rates are relatively low. In addition, thin soils at the base of slopes can become saturated and initiate flow into the underlying fractures. Because of relatively thick soils (greater than 6 m, or 20 ft) and relatively high evapotranspiration, terraces contribute the least to net infiltration. Although channels occupy a very small portion of the site area, they do have the potential to contribute significant, localized pulses of net infiltration when runoff occurs. Overall, net infiltration at Yucca Mountain is an episodic, transient process that depends primarily on the length of time that saturated or near-saturated conditions exist at the soil-bedrock interface and on the effective conductivity of the underlying bedrock (Flint et al. 1996).

A model was developed to calculate net infiltration at Yucca Mountain using two data sets: physiographic and hydrologic information and measurements or estimates of daily precipitation (Flint et al. 1996). Using this information, the model calculates daily net infiltration using a water-balance approach, considering the water available for infiltration, and calculating the net infiltration based on the effective hydraulic conductivity of the bedrock. The model was calibrated using daily precipitation records (1980 through 1995) for the site and corresponding records from the moisture measurement boreholes (Flint et al. 1996). Infiltration simulations were performed for the present-day and for possible future, wetter climates. The simulations used precipitation models based on four regional precipitation stations, one near Yucca Mountain for present-day climate and three more distant stations representing possible future climates.

Present-day average annual net infiltration rates were estimated for a large area (approximately 228 $km^2$ or 88 $miles^2$) surrounding Yucca Mountain (CRWMS M&O 1998d, Section 5.3.4.1.5.1). For repository performance calculations, infiltration rates were estimated for a smaller (43 $km^2$, or 17 $miles^2$) area centered on the repository. Over the area of this model, shown in Figure 2-16, net infiltration averages approximately 4.9 mm (0.20 in.) per year (Bodvarsson et al. 1997). Infiltration ranges from 0 mm (0 in.) per year in washes where the soil is 6 m (20 ft) thick or greater to approximately 40 mm (1.6 in.) per year near the Prow of Yucca Mountain. For an 11.6-$km^2$ (4.5-$mile^2$) area centered over the potential repository, estimated net infiltration averages about 6.0 mm (0.25 in.) per year and ranges from 0 mm (0 in.) per year for locations with thick soils to over 20 mm (0.78 in.) per year along the crest of Yucca Mountain. For the potential repository area covered by the dense model grid, net infiltration averages 6.7 mm (0.26 in.) year (Bodvarsson et al. 1997). These results address the NRC subissue on the spatial distribution of present-day shallow groundwater infiltration, which is part of the Key Technical Issue on Unsaturated and Saturated Flow Under Isothermal Conditions (NRC 1997a) (see Volume 4, Section 4.3.3.9).

To evaluate the effects of potential future climates on net infiltration, daily precipitation records from two locations in the south-central Basin and Range were used: Rainier Mesa, Nevada, and South Lake, California (CRWMS M&O 1998d, Section 5.3.4.1.5.3). Both locations are at higher latitudes and elevations than Yucca Mountain and are considered to be reasonable precipitation analogs for potential future climates at Yucca Mountain. The Rainier Mesa, Nevada, site represents the long-term precipitation average for future climatic conditions including the next glacial cycle that can be expected at Yucca Mountain. Estimated average annual net infiltration for the Rainier Mesa, Nevada, wetter climate analog, with 289 mm (11 in.) per year precipitation, was approximately 33 mm (1 in.) per year. For the area centered over the potential repository, this calculation indicated maximum annual infiltration of more than 150 mm (6 in.) per year for the upper headwaters of several drainages. The South Lake analog site represents climatic conditions at Yucca Mountain under possible future superpluvial conditions, the wettest conditions believed likely at Yucca Mountain. Estimated average annual net infiltration for the superpluvial, with 427 mm (17 in.) per year precipitation, was about 108 mm (4 in.) per year for the area centered over the potential repository, with a maximum of 706 mm (28 in.) per year. In general, results obtained using the model for present-day and possible wetter conditions are in

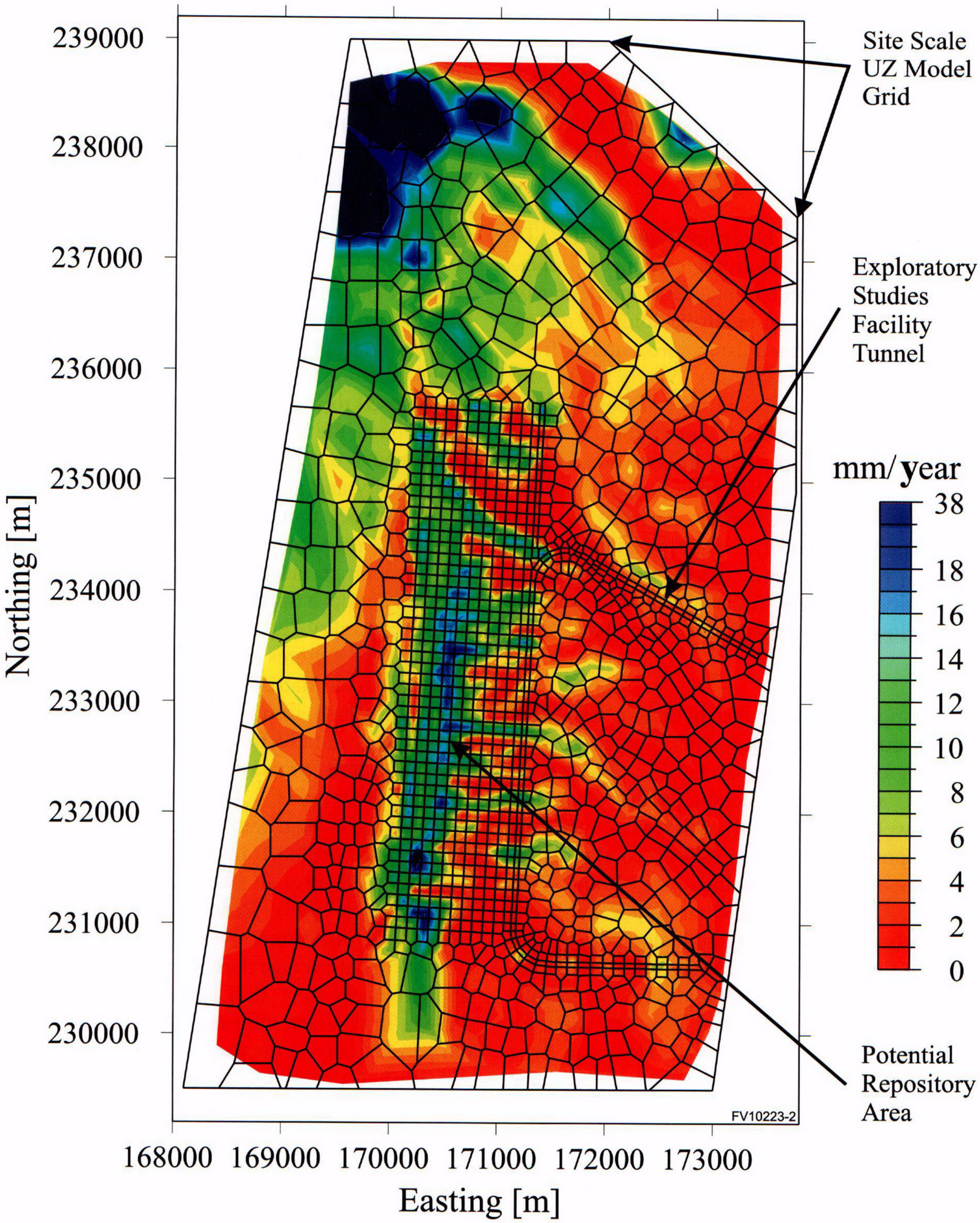


Figure 2-16. Distribution of Simulated Present-Day Average Annual Net Infiltration at Yucca Mountain from the Scaled 100-Year Stochastic Precipitation Model in Millimeters per Year (mm/year) (Source: CRWMS M&O 1998d)

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reasonable agreement with estimates of net infiltration and recharge in the Yucca Mountain region obtained using alternative methods (CRWMS M&O 1998d, Section 5.3.4.1.5.3). These results address the NRC subissue on the likely hydrologic effects of climate change, which is part of the Key Technical Issue on Unsaturated and Saturated Flow Under Isothermal Conditions (NRC 1997a) (see Volume 4, Section 4.3.3.9).

**Matrix Properties of Hydrogeologic Units.** To define a physical and hydrologic properties database adequate for three-dimensional modeling of the unsaturated zone, an intensive study of matrix properties was performed using core samples from 31 boreholes (Flint 1998, p. 11). Nearly 5,000 core samples were analyzed in the laboratory to measure important hydraulic properties. These properties included porosity (a measure of the amount of void space within the rock which determines how much water a rock can absorb), bulk density, particle density, water content, water potential, saturated and unsaturated hydraulic conductivity (measures of the ability of the rock to transmit flow), and moisture-retention characteristics.

The investigations show that hydraulic properties generally correspond well to rock properties such as the degree of welding of a rock. The lowest porosities and matrix conductivities occur in densely welded tuffs and vitrophyres, and the highest porosities and matrix conductivities occur in nonwelded and bedded rocks (Flint 1998, pp. 3–21). The porosity and saturation data were used to define 30 detailed hydrogeologic units. For numerical flow models, parameter values were calculated for each unit for all measured properties (Flint 1998, p. 43). In general, porosity variation within each unit is relatively small. However, large variations in saturated hydraulic conductivity have been noted in welded units because of variable microfracture densities and mineral alteration.

Abrupt changes in hydrologic properties in the unsaturated zone may cause downward percolating water to divert laterally in the unsaturated zone. Such diversions, which may be caused by natural capillary action (high suction potential, like a sponge) or by a low permeability barrier that impedes flow, may exist at Yucca Mountain (Flint 1998, pp. 9–10). The Paintbrush nonwelded tuff is situated between two welded and fractured ash flow units (Tiva Canyon and Topopah Spring tuffs). The contacts of the nonwelded units are characterized by large variations in porosity and saturated hydraulic conductivity. Preliminary analysis suggests significant lateral flow is possible within the Paintbrush nonwelded unit even with a relatively low vertical percolation flux of only 1 mm (0.04 in.) per year (Moyer et al. 1996, p. 80).

**Rock Properties from Air-Injection Tests.** Unsaturated zone air-injection testing measures the bulk (or total) permeability of the rock mass to air. When combined with other information, these data can be used to analyze the flow of both water and gas through the proposed repository. Tests were performed to determine field-scale bulk permeability, porosity and anisotropy (spatial variability) of the major rock units above, below and within the potential repository horizon (LeCain 1997). Air-injection permeability values in the Tiva Canyon and Topopah Spring welded tuffs show considerable variability, reflecting the heterogeneous distribution of fractures and the low permeability of the intact rock matrix. Air-injection permeability values obtained from the Paintbrush nonwelded unit are less variable than the welded tuffs, indicating that matrix properties generally control flow through these units. Air-permeability investigations have also been performed in Tiva Canyon tuff in boreholes drilled from the Exploratory Studies Facility (LeCain et al. 1997; LeCain and Patterson 1997; LeCain 1998). Results indicate that the permeability is anisotropic (variable in different directions) with an average horizontal to vertical ratio of approximately 10:1 (LeCain et al. 1997; LeCain 1998). In contrast, the ratio of horizontal to vertical permeability in the deeper Topopah Spring tuff is 1:10 (LeCain 1997).

**Pneumatic Pressure and Gaseous-Phase Flow.** Measurements of pneumatic (air) pressure, water potential, and temperature in the unsaturated zone provide important information about the flow of gases (including water vapor) and liquid at depth. Instruments were placed in 11 deep boreholes to monitor conditions throughout the unsaturated zone. The monitoring data were analyzed to determine the following:

- Gas flow properties and vertical permeability of major hydrogeologic units
- Properties of faults and fracture zones·
- Flow of gas and water vapor through the deep unsaturated zone·
- Effects of Exploratory Studies Facility construction on the gaseous-phase system (Rousseau et al. 1996)

The unsaturated zone at Yucca Mountain comprises four distinct pneumatic layers (Rousseau et al. 1996), which are consistent with the major hydrogeologic units defined for the site (welded Tiva Canyon tuff, nonwelded Paintbrush tuff, welded Topopah Spring tuff, and nonwelded Calico Hills tuff). The Tiva Canyon welded unit is subject to very rapid transmission of atmospheric-pressure changes throughout its volume, with little attenuation (Rousseau et al. 1996). Because of its direct surface exposure to the atmosphere, gas flow is strongly influenced by topographic and barometric-pumping effects. In contrast, the Paintbrush nonwelded unit significantly attenuates (lessens) the downward transmission of atmospheric-pressure changes, although the degree of attenuation varies over the Yucca Mountain site area (Rousseau et al. 1996; Patterson et al. 1996). Attenuation of pressure changes in the Paintbrush nonwelded unit generally decreases from north to south (Patterson et al. 1996). The decrease is attributed in part to variation in thickness of the unit, which thins to the south, and also to local differences in saturation and/or the presence or absence of open fractures (Rousseau et al. 1996; Patterson et al. 1996).

Throughout the site area, borehole data indicate that pressure signals transmitted through the Paintbrush nonwelded unit are propagated nearly instantaneously throughout most of the entire vertical section of the Topopah Spring welded unit (Rousseau et al. 1996; Patterson et al. 1996). This indicates that the fractures within the Topopah Spring welded unit are permeable and highly interconnected within both the lithophysal and nonlithophysal units. In fact, in some locations, pressure signals are detected at depth more quickly than in the Paintbrush unit (reversing the normal trend of attenuation). This is probably caused by the pressure signal bypassing the Paintbrush nonwelded unit by traveling preferentially down the Drill Hole Wash fault and the Ghost Dance fault (Patterson et al. 1996). Pressure data from the deepest boreholes at Yucca Mountain indicate that essentially all remaining atmospheric-pressure signals are attenuated by the Calico Hills nonwelded unit (Patterson et al. 1996). The Calico Hills nonwelded unit contains perched-water zones, with extremely low permeability to air, that effectively impede the downward propagation of the signal.

Based on pressure monitoring data, the pneumatic properties of the unsaturated hydrogeologic units have been calculated and compared to the results of the above air injection tests. The comparisons indicate general agreement, with the Tiva Canyon welded unit and Topopah Spring welded unit having significantly greater permeabilities than the Paintbrush nonwelded unit. However, values calculated from the pneumatic data generally are one or two orders of magnitude greater than those obtained from the air-injection tests, probably because the air injection tests mainly measure the horizontal permeability. The pneumatic data mainly reflect the vertical permeability (Rousseau et al. 1996, Section 3.2.3.2). Overall, these comparisons imply that there is significant anisotropy in air permeability in the welded tuffs. In the Tiva Canyon welded unit, the ratio of horizontal to vertical permeability (about 10:1) is attributed to the presence of subhorizontal unloading fractures in the shallow subsurface. In the deeper Topopah Spring welded unit, the permeability ratio is reversed, probably because of the lesser abundance of subhorizontal fractures.

Pneumatic-pressure interference effects associated with excavation of the Exploratory Studies Facility by the tunnel-boring machine were monitored. These effects provide insight on the response of the overall unsaturated zone gaseous-phase system to pressure changes. Significant pneumatic-pressure interference effects were observed at three locations (Patterson et al. 1996):

- Penetration of the Paintbrush nonwelded unit
- Crossing of an unnamed fault about midway down the north ramp
- Crossing of the Drill Hole Wash fault near the intersection of the north ramp and main drift

In general, excavation of the Exploratory Studies Facility caused a significant decrease in the attenuation of the atmospheric-pressure signal measured in the Topopah Spring welded unit (i.e., pressure changes were transmitted downward more rapidly after excavation). Consistent with previous findings, monitoring pneumatic-interference effects demonstrated the following (Patterson et al. 1996):

- The Paintbrush nonwelded unit is a significant pneumatic impeding layer.
- The vertical permeability of the Topopah Spring welded unit is very large.
- While some faults in the Topopah Spring transmit pneumatic-pressure signals quickly over significant horizontal distances, other faults act as low-permeability barriers.
- The pneumatic properties of the Topopah Spring welded unit can differ considerably on either side of a fault.

**Distribution of In Situ Water Potential.** Monitoring water potential (also known as suction or capillary pressure) provides important information concerning hydrologic conditions throughout the unsaturated zone. Water potential is a measure of the ability of the rock to take on additional water through capillary forces. In combination with total porosity (the volume available to be filled with water), the water potential controls the amount of water that a rock can imbibe (or absorb). Rocks with high water potentials are nearly saturated and are not able to absorb more water in their matrix; therefore, water in fractures in such rocks will tend to flow quickly through the unsaturated zone. Water potential has been monitored at multiple depths in six boreholes at Yucca Mountain since 1994 (Rousseau et al. 1997).

Water potential profiles measured in the Paintbrush nonwelded and the upper Topopah Spring welded units are similar, suggesting that the units are generally in equilibrium and that water flow is not diverted by the contact between them. However, in Pagany Wash, northeast of the repository area, the data suggest that lateral flow may be occurring in the Paintbrush nonwelded unit at depths of several hundred feet. This may be the result of recharge from the channel during wet years or large precipitation events. This interpretation is consistent with tritium data (Yang et al. 1996).

Although moisture conditions and potentials are generally stable across the site, several transient (temporary) shifts in both water potential and temperature have been detected. These changes were probably caused by topographically induced, density-driven gas flow originating above the Paintbrush nonwelded unit (Rousseau et al. 1997) and resulted in moisture redistribution in the fractures of the Tiva Canyon welded unit.

In the southern part of the site, moisture conditions are both similar to and different from the north. As in the north, water potentials are high and generally in equilibrium, but the data indicate that the rock mass in the south is a little drier. The differential rates of water-potential response to the construction of the Exploratory Studies Facility indicate the presence of a dense network of interconnected fractures in the upper Topopah Spring welded unit (Rousseau et al. 1997). Also, evidence of barometric pumping (gas flow driven by atmospheric pressure changes) is readily apparent at the base of the Paintbrush nonwelded unit.

A borehole was drilled in the Ghost Dance fault zone east of the Exploratory Studies Facility main drift to test the effect of the fault on hydrologic conditions. The fault has apparently caused different water-potential recovery trends in units of the Topopah Spring welded unit above and below the fault (Rousseau et al. 1997). The Topopah Spring welded unit near the fault is less isolated from the atmosphere than elsewhere, probably caused by higher fracture densities in the Paintbrush nonwelded unit. This enhanced connection to the atmosphere results in a moisture regime that is more dynamic than elsewhere with both rapid percolation of liquid water and drying caused by barometric pumping (Rousseau et al. 1997, p. 62).

Overall, water potentials within the Tiva Canyon welded unit reflect relatively dry conditions at shallow depths and progressively wetter conditions with increasing depth. This results in decreased imbibition with depth and upward matrix flow (Rousseau et al. 1997). These observations do not preclude episodic, downward fracture-flow; in fact, the data from the Paintbrush nonwelded and Topopah Spring welded units are consistent with downward percolation of moisture. Water potentials in the Topopah Spring welded unit generally are high and do not change significantly with depth (Rousseau et al. 1996). The relatively high water potentials indicate that the rock matrix is sufficiently wet to infer that water flowing in fractures will generally not be imbibed by the rock. Data also indicate that potential gradients in the Topopah Spring welded unit are very low, so the gravitational potential is dominant and percolation will generally be vertically downward (Rousseau et al. 1996).

**Hydrochemical and Isotopic Indications of Fluid Flow.** Hydrochemical and isotopic data have been collected and interpreted to provide constraints on possible fluid-flow mechanisms and fluid residence times in the unsaturated zone at Yucca Mountain (Yang et al. 1996; 1997). The data include major-ion aqueous concentrations, whole gas compositions, and aqueous and gaseous isotopic content. In spite of the large distances separating boreholes, chemical compositions of pore-water samples generally are similar within a given stratigraphic unit and markedly dissimilar between different host lithologies in any given borehole. The total concentration of major ions in pore water samples is highly variable and often is greater near lithostratigraphic contacts than in the middle of rock units. This suggests significant rock-water interaction and prolonged contact of percolating water with silicate rocks. Further, unsaturated zone pore water has significantly larger concentrations of total dissolved solids than does either perched water or saturated zone water (Yang et al. 1996; 1997).

The concentration of chloride in pore water of the Paintbrush nonwelded unit, especially deeper within the unit, is one to two orders of magnitude greater than either perched water or saturated zone water. Low concentrations of chloride are probably indicative of little rock-water interaction or less evaporation. This would be consistent with a fracture flow origin through the Paintbrush nonwelded unit. The composition of pore water within the nonwelded units (Paintbrush and Calico Hills) does not change uniformly with depth as would be expected from vertical percolation and rock-water interaction. Therefore, the data may suggest some lateral flow within the nonwelded units.

Chloride concentrations in the Calico Hills nonwelded unit are substantially lower than those in the overlying Paintbrush nonwelded unit. These concentrations are possibly because of differences in the amounts of evapotranspiration relative to infiltration undergone by infiltrating water or differences in infiltration mechanisms or topographic settings (CRWMS M&O 1998d, Section 5.3.4.3.1.4). The isotopic composition of strontium in pore water samples varies less erratically than the major ion chemistry and suggests some degree of rock-water interaction (Marshall et al. 1997). Pore water samples within the Paintbrush nonwelded unit become markedly more radiogenic with depth, possibly caused by longer reaction times.

High tritium concentrations released during past atmospheric nuclear weapons testing serve as a tracer to identify young water (post-1952) worldwide, not just at Yucca Mountain. High tritium concentrations were found in pore water samples collected from the Bow Ridge fault in an alcove constructed off the Exploratory Studies Facility north ramp (LeCain et al. 1997). The data indicate that water has migrated to depths of at least 20–30 m (66–98 ft) in the past 40 years, which is consistent with the conceptual model of flow at the site. Fast infiltration paths are expected to be associated with faults and other major structural features. The geologic data at the Bow Ridge fault (including extensive calcite and silica mineral deposits) clearly demonstrate that the fault is a major pathway for infiltration. Tritium data for samples from deeper in the unsaturated zone show several inversions (Yang et al. 1996; 1997) where higher tritium concentrations occur below lower concentrations. These inversions have been interpreted to indicate that younger water has migrated to depth more rapidly than the water in overlying units. This would suggest that flow in fractures and/or lateral flow must be significant. Post-bomb (post-1952) tritium has been detected at considerable depth (Prow Pass tuff) in the unsaturated zone in only one borehole located approximately 1 km (0.6 mile) east of the potential repository area in a highly faulted region. The presence of calcium-bicarbonate type pore water at the same depth suggests that younger water from a shallow depth was transported through fractures with little contact or reaction with the zeolitic unit of the Calico Hills nonwelded unit.

Chlorine-36 is another isotope produced by atmospheric weapons testing (mainly in the Pacific Ocean from 1952-1958) that hydrologists have used to identify relatively young waters. Over 700 chlorine-36 samples from soil, rock and water, and packrat middens (fossilized nests) have been collected and analyzed at the site (Fabryka-Martin et al. 1997a; Fabryka-Martin et al. 1998). Investigations have confirmed that thick alluvium reduces net infiltration (Fabryka-Martin et al. 1998) and samples of rocks underlying thick alluvium indicate no evidence of bomb-pulse chlorine-36. Fast transport through the Tiva Canyon welded unit is indicated by bomb-pulse chlorine-36 detected in several boreholes that intersect the Paintbrush nonwelded unit The existence of fast pathways into the Topopah Spring welded unit is indicated by the detection of bomb-pulse chlorine-36 at 31 of 247 locations sampled in the northern half of the Exploratory Studies Facility (Fabryka-Martin et al. 1997a). The apparent correlation of bomb-pulse chlorine-36 anomalies with faulting indicates that the anomalies may be caused by fracture flow through the Paintbrush nonwelded unit followed by transport in fractures through the Topopah Spring to the Exploratory Studies Facility.

Most of the samples from the Exploratory Studies Facility did not contain any bomb-pulse chlorine-36. Chlorine-36 contents generally indicated travel times greater than 10,000 years in the northern part of this facility, and less than 10,000 years in the southern part. A few samples from the southern part of the Exploratory Studies Facility had chlorine-36 content significantly below the present-day background, possibly suggesting the presence of relatively stagnant water. None of the few chlorine-36 measurements for samples collected from below the potential repository horizon have detected bomb-pulse chlorine-36. Flow and transport modeling (Fabryka-Martin et al. 1997a; Robinson et al. 1996) has confirmed that numerical models of the site with reasonable parameter estimates can simulate observed chlorine-36 signals. The transport modeling is consistent with the following observations:

- Infiltration is spatially variable and appears to average more than 1 mm (0.04 in.) per year over the potential repository block.

- Fracture transport probably is pervasive, permitting rapid transport through otherwise low-conductivity materials.

- Isolated fast paths associated with faults and fractures probably penetrate deep into Yucca Mountain.

Pore water samples from the Paintbrush and Calico Hills nonwelded units have significant amounts of modern carbon suggesting apparent ages of less than 10,000 years (Yang et al. 1996; 1997). However, the apparent ages may represent either a single episode of inflow or a mixing of older and younger pore water. The stable isotope composition of pore water samples is similar to local precipitation suggesting very little evaporation occurred before infiltration. Pore water is also not similar to summer storm precipitation. This suggests that it may have originated as snow or rain during the colder months of the year (Yang et al. 1997). Stable isotope data for the basal vitrophyre of the Topopah Spring tuff suggest a mixture of glacial-age and modern water although pore water both above and below seems to be of younger post-glacial origin.

Gas samples collected periodically between 1988 and 1994 from a deep borehole indicate very consistent carbon-14 composition as a function of time with a gradual decrease in the percent of modern carbon with depth (Yang et al. 1996). The data indicate that the transport velocity of gas within the Paintbrush nonwelded unit is much slower than in the Topopah Spring welded unit probably because of the greater water content and lower fracture density. Overall, the relation between carbon-14 ages and depth indicates that atmospheric carbon dioxide has moved downward through the unsaturated zone primarily by simple diffusion. The apparent lack of equilibrium between gaseous and liquid phases for carbon isotopes is consistent with the conceptual model that most of the water percolating through the unsaturated zone is episodic and rapid; such fracture flow does not equilibrate with the gaseous phase (Yang et al. 1996; 1997).

Water percolating through the unsaturated zone at Yucca Mountain leaves secondary minerals within the fracture network and in lithophysal cavities. Secondary minerals are deposited in areas where solutions exceed chemical saturation with respect to various mineral phases, most commonly calcite and opal. The composition and age of the minerals provides information on the chemistry and timing of flow through the mountain. Based on thorium-230/uranium activity ratios (Paces et al. 1996b; 1997; 1998), ages of outer surfaces of most secondary minerals in the Exploratory Studies Facility range from 28,000 years to more than 500,000 years, with a median age of approximately 200,000 years. Apparent carbon-14 ages of the latest calcite surfaces range from 16,000 years to 52,000 years, with a median age of 33,000 years.

**Estimation of Percolation Flux.** One of the most important parameters for modeling the long-term performance of a repository at Yucca Mountain is the rate of water flow through the mountain, particularly at the proposed repository horizon. This parameter is known as the percolation flux, and it controls the rate at which waste packages may be exposed to water, the rate at which the packages will fail, and ultimately the rate at which radionuclides could be released from the repository. Clearly, the understanding of flux rates is very important to YMP's ability to assess reasonable future performance. Therefore, the rate of percolation has been estimated using a variety of methods that depend on physical, chemical, isotopic, and hydrologic data (CRWMS M&O 1998d, Section 5.3.4.3.1). These methods include the following:

- Temperature and heat flow
- Matrix saturations and water potentials
- Gaseous and aqueous carbon-14 equilibrium
- Perched water volumes and residence times
- Complete-mixing chloride mass-balance model for Paintbrush nonwelded unit, Calico Hills nonwelded unit, and perched water
- Dual-permeability formulation of the basic chloride mass-balance model

Flux estimates from various methods differ widely, primarily as a result of how and how well they consider and account for fracture flow versus matrix flow. One method (the temperature/heat flow method) is not sensitive to whether flow occurs in fractures or matrix. Temperature is a function of total mass flux, regardless of where flow occurs, and thermal conductivity is a function of saturation, which does not vary significantly with depth throughout most of the unsaturated zone. Based on temperature/heat flow data, mean percolation flux values appear to be on the order of 10 mm (0.4 in.) per year (CRWMS M&O 1998d, Section 5.3.4.3.1.2).

In general, low flux estimates were obtained using the matrix saturation and water potential methods (means of 0.1 and 0.02 mm, or 0.004 and 0.0008 in., per year) and the perched water volumes and residence times method, which yielded a mean of 0.5 mm (0.02 in.) per year. Intermediate flux values were obtained using the gaseous and aqueous carbon-14 equilibrium method (a mean of 5.8 mm, or 0.23 in. per year) and the complete mixing, chloride mass-balance model for the Paintbrush and Calico Hills nonwelded units. These methods yielded estimates of 1.7 and 3.5 mm, or 0.07 and 0.14 in., per year. Relatively high percolation estimates (an average of 17.8 mm, or 0.7 in.

per year) were obtained using the complete mixing, chloride mass-balance model for perched water. For the dual-permeability chloride mass-balance model, the sitewide average percolation flux was estimated to be 9.8 mm (0.4 in.) per year. Only 0.7 and 1.7 mm (0.03 and 0.07 in.) per year of this was matrix flow through the Paintbrush nonwelded unit and Calico Hills nonwelded unit with the remainder being flow through fractures and faults.

Estimates of percolation flux using the temperature and heat flow method are consistent with the relatively high infiltration fluxes estimated for Yucca Crest (Flint et al. 1996). However, these estimates indicate that net infiltration in some washes may be greater than currently predicted by the numerical infiltration model. An updated version of the infiltration model that accounts for cumulative runoff has calculated greater infiltration rates at the base of side slopes adjacent to washes, which may account for the discrepancy.

Overall, there is reasonably good agreement between the estimates of net infiltration (Flint et al. 1996) and percolation flux determined by the various methods (CRWMS M&O 1998d, Section 5.3.4.3.1). Although both methods indicate that approximately 6 percent or less of the average annual precipitation of 170 mm (6.7 in.) per year at Yucca Mountain becomes net infiltration, the methods differ in predictions of the spatial distribution of flux. The differences may reflect true spatial variability, or they may be a function of the sensitivity of the method to the fracture component of the flux. For example, the low fluxes calculated using matrix saturation and water potential methods ignore the flow that may occur in fractures that are not in equilibrium with the matrix, and therefore, underestimate the total flux. The simple arithmetic average of the mean percolation-flux values of all the subsurface methods (excluding those using matrix saturations and water potentials) is 7.0 ± 6.0 mm (0.3 ± 0.24 in.) per year. This compares with the estimated average present-day annual infiltration rates of 4.9 mm (0.2 in.) for the area of the site-scale unsaturated zone model and 6.7 mm (0.3 in.) for the potential repository area. Figure 2-17 shows the modeled distribution of percolation at the repository horizon. Given the complexity of the problem and the relatively large standard deviation of the percolation flux, the average net infiltration and estimates of percolation flux are in relatively good agreement. The results on percolation flux address the NRC subissue on the spatial distribution of present-day groundwater percolation through the proposed repository horizon. This is part of the Key Technical Issue on Unsaturated and Saturated Flow Under Isothermal Conditions (NRC 1997a) (see Volume 4, Section 4.3.3.9).

**Perched Water.** The presence and distribution of perched water (zones saturated with liquid water at elevations higher than the regional water table) at Yucca Mountain may be significant because of the potential effect of such zones on repository performance. Perched water bodies may form where abrupt vertical variations in hydrologic properties cause ponding of water, where faults or other structural discontinuities prevent the drainage of percolating water, or from a combination of these two natural conditions. Liquid water above the repository horizon could potentially be available to percolate downward and dissolve and transport waste. Perched zones below the repository could conceivably provide a transport pathway for water migrating away from the repository.

Based on field observations in boreholes and in the Exploratory Studies Facility, the existence of perched water at elevations above the repository horizon is believed to be unlikely. However, perched water has been found in several locations below the potential repository (Striffler et al. 1996; Rousseau et al. 1996). Near Drill Hole Wash, perched water occurs above the contact of the crystal-poor lower nonlithophysal zone and the crystal-poor vitric zone of the Topopah Spring tuff. This contact is approximately 100–200 m (328–656 ft) below the potential repository horizon. The cause of the perched zone is uncertain; it may be related to the low permeability of the vitric zone or of the underlying, relatively unfractured Calico Hills tuff. Alternatively, a northeast trending fault, which acts as a lateral barrier to flow, may cause the perched water. Pumping tests conducted in one of the boreholes indicated that the

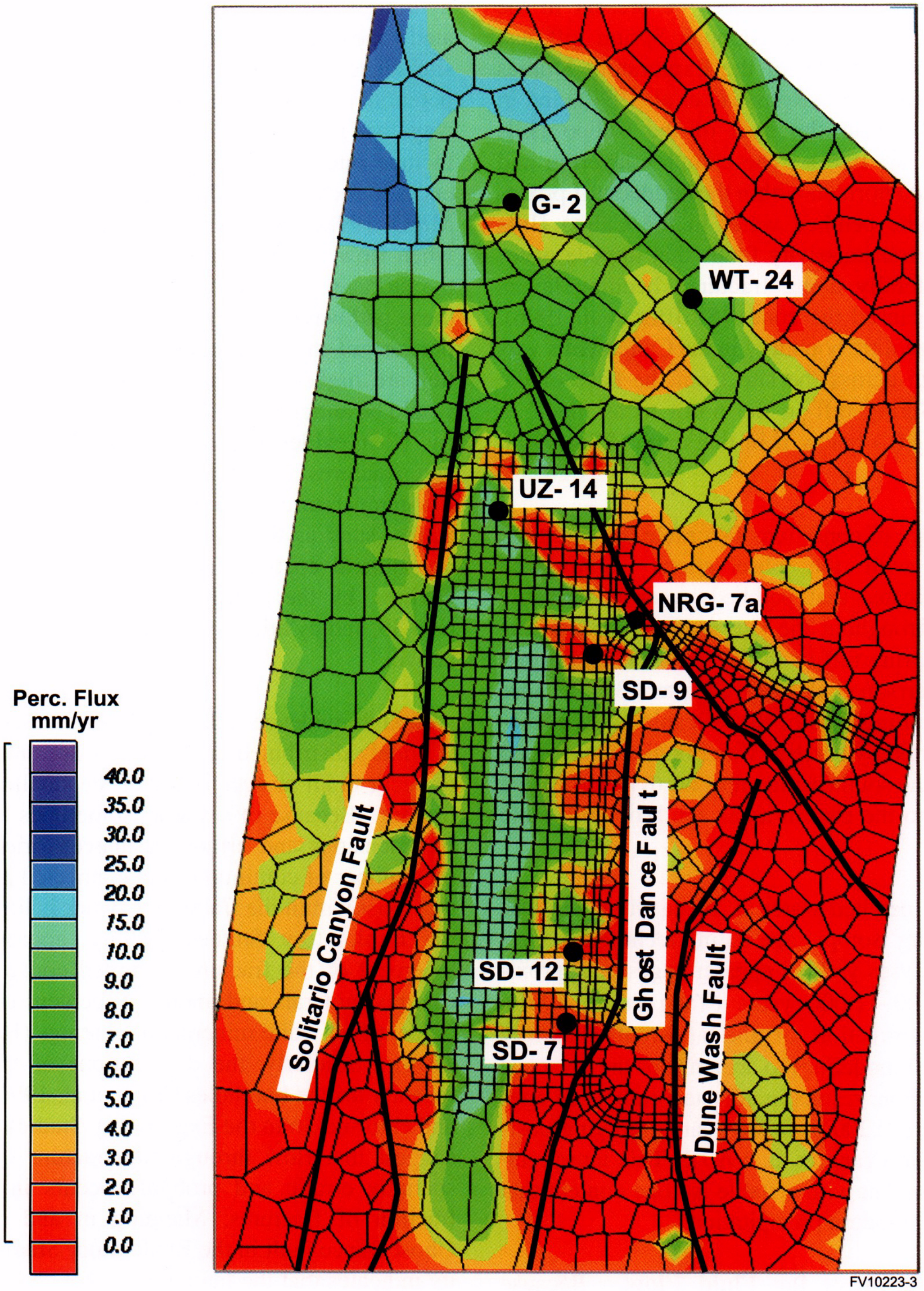


Figure 2-17. Model of Calculated Percolation Flux at the Potential Repository Horizon Including Key Boreholes and Faults
(Source: Bodvarsson et al. 1997)

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perched-water reservoir might be extensive (Striffler et al. 1996).

Perched-water zones may also be present in the basal vitrophyre of the Topopah Spring tuff just south of the midpoint of the Exploratory Studies Facility's main drift (Rousseau et al. 1997), and in bedded tuffs near the base of the Calico Hills (Striffler et al. 1996). The complex layering and the zeolitized horizon within the bedded tuff probably cause the perched water in the Calico Hills unit. Low transmissivity faults that impede water flowing laterally along fractured bedding layers may have caused the zones (Striffler et al. 1996). The vitric/zeolitic boundary in the Calico Hills varies in depth across the site from the base of the Topopah Spring tuff in the north to as much as 140 m (459 ft.) below it in the south (Flint 1998, p. 39).

The presence of conditions favorable for perching, combined with the observations summarized above, indicates that perched water is probably common throughout the site near the base of the Topopah Spring tuff or in the Calico Hills Formation (Bodvarrson et al. 1997, Chapter 13). Because of the prevailing dips of the volcanic units, percolation diverted by perched water bodies would tend to flow to the southeast in areas north of Drill Hole Wash and to the east in areas south of Drill Hole Wash.

The age of perched water at Yucca Mountain was studied using isotopic age dating techniques. Carbon-14 analyses yielded apparent ages of approximately 3,500–11,000 years (Yang et al. 1996). However, correction of the apparent ages (by geochemical modeling) to account for the presence of older carbon, results in adjusted carbon-14 ages ranging from 2,200 to 6,300 years, implying postglacial origin (Yang et al. 1997). This interpretation is consistent with a stable isotope content that is similar to modern precipitation.

**Discrete Pathways for Fluid Flow.** Because assessments of the release and transport of radionuclides from a repository are directly dependent on the amount, location and rate of flow of water in the system, a credible understanding of flow processes is requisite to any successful analysis. Although flow in discrete pathways such as faults and fractures may complicate analysis of the hydrology, the free draining nature of the unsaturated zone has been recognized as an attribute of the site since Yucca Mountain was identified as a potential repository (see Section 1). Discrete pathways are present at a variety of scales, and may include interconnected fractures, faults, or differences in rock unit welding and alteration (CRWMS M&O 1998d, Section 5.3.4.3.2.2). In general, when flow occurs in discrete pathways, much of the storage capacity of the rock is bypassed. If these pathways are continuous through significant portions of the unsaturated zone, transport velocities are higher and travel times are shorter than would be anticipated on the basis of the total porosity. Clear evidence that water moves through faults and fractures is provided by the abundance of low-temperature mineral deposits in major fault zones (such as the Bow Ridge fault), by secondary-mineral coatings in fractures and lithophysal cavities, by the distribution of tritium and chlorine-36, and by other hydrochemical data discussed above.

Although evidence indicates that flow in fractures is widely distributed at the site, it does not appear to occur in all or even many of the small fractures present. Because of variable, sometimes low fracture densities and erratic or uneven orientations, the number of continuous and connected pathways that exist within the fracture network is limited. In the Exploratory Studies Facility, approximately 9 percent of the fractures sampled contained calcareous minerals and another 9 percent contained unidentified white minerals or coatings (Barr et al. 1996). Similarly, the distributions of tritium in recently drilled boreholes (Yang et al. 1996; 1997), and chlorine-36 in the Exploratory Studies Facility, suggest that flow through the fracture system is spatially erratic and probably occurs in a small fraction of fractures. Mapping in and near the Ghost Dance fault in the Exploratory Studies Facility indicates that the fault zone is not characterized by more abundant secondary mineral deposition than adjacent unfaulted rock. This observation suggests that the volume of flow through the Ghost Dance fault, at and above the level of the Exploratory Studies Facility, is probably similar to surrounding rock. This implies that the Ghost Dance fault is not a major pathway for water flow. However, the presence of chlorine-36 anomalies in the Exploratory Studies Facility near the fault may indicate that at least some pathways for rapid transport are present.

Because of their vertical extent, faults have the potential to intercept and divert gas and liquid moving through all unsaturated zone units, and they may account for a significant fraction of the overall moisture balance in the unsaturated zone (CRWMS M&O 1998d, Section 5.3.4.3.2.2). The presence of chlorine-36 and tritium in the Exploratory Studies Facility, and deep in surface-based boreholes, indicates that faults allow some water to bypass the matrix of the Paintbrush nonwelded unit. Pneumatic monitoring of deep boreholes indicates that the permeability of the Paintbrush nonwelded unit has been significantly enhanced near faults (Rousseau et al. 1996; CRWMS M&O 1998d, Section 5.3.4.3.2.2). The very young age of pore water samples 490 m (1,608 ft) deep in a borehole approximately 1 km (0.6 mile) east of the potential repository area suggests rapid vertical transport in an intensely faulted area. Similarly, the relatively low chloride concentrations of water in the saturated zone suggests that a significant component of dilute water must be bypassing the zeolitic matrix of the Calico Hills and Prow Pass tuffs by moving downward through faults (CRWMS M&O 1998d, Section 5.3.4.3.2.2).

**Fracture-Matrix Interaction.** The degree of interaction between water in fractures and the rock matrix has important implications for several aspects of flow and transport. If there is substantial interaction, flow in fractures could be attenuated by matrix imbibition (suction into the rock). Also, radionuclide transport could be significantly retarded or slowed by interaction with minerals in the matrix that can absorb radionuclide molecules. In contrast, limited interaction between fractures and matrix may result in rapid flow in fractures with little or no retardation of dissolved species. Evidence concerning the degree of fracture-matrix interactions is based largely on circumstantial evidence provided by geochemical data, water-potential measurements, and observations of the character of fracture coatings (CRWMS M&O 1998d, Section 5.3.4.3.2.4). The presence of bomb-pulse tritium and chlorine-36 deep in the unsaturated zone demonstrates that interaction between water in fractures and matrix is limited; nevertheless, some degree of interaction must occur or these tracer isotopes would not be detected in the rock matrix.

Although the presence of bomb-pulse chlorine-36 in the Exploratory Studies Facility suggests flow in faults that bypass the Paintbrush nonwelded unit, intermediate chlorine-36 values may be the result of a small amount of bomb-pulse water mixing with other recent water. This interpretation implies that attenuation of infiltration by the Paintbrush nonwelded unit is less than complete. This conclusion is consistent with the analysis of chloride data from the unsaturated zone and shallow saturated zone. This analysis suggests that, as a result of water movement down fractures and faults, 80–90 percent of total percolation flux bypasses the matrix of the Paintbrush nonwelded and Calico Hills units.

The lack of substantial interaction between fractures and matrix is demonstrated in deep boreholes in which fracture and matrix water collected from the same borehole interval were not in chemical equilibrium. Further, relatively high water potentials, measured throughout much of the unsaturated zone, indicate the absence of strong water-potential gradients needed for matrix imbibition of fracture water.

**Three-Dimensional Unsaturated Zone Modeling.** Unsaturated zone flow modeling studies for Yucca Mountain have relied on the extensive database available for the Yucca Mountain site area. These data include those on liquid saturation, in situ and core-sample water potential, saturated conductivity and water-retention curves, rock-property measurements, in situ pneumatic pressure, borehole temperature, air permeability, geochemical and isotopic characteristics, perched water, Exploratory Studies Facility fracture mapping, and fracture coatings (Bodvarsson et al. 1997, Chapter 1). Incorporating this data into modeling studies has resulted in a comprehensive and complex three-dimensional unsaturated zone model. This model represents important flow processes including moisture flow, capillary pressure effects, gas flow, convective and conductive heat transfer, evaporation and condensation, moisture and gas flow travel times, and transport of conservative and reactive species in the mountain.

**Model Structure, Formulation, and Upper Boundary Condition.** In general, the model layers and grid represent the important details of the major hydrogeologic units and structures including zones of zeolitic alteration, faults and their offsets, dipping beds and eroded units. The numerical model grid covers approximately 43 $km^2$ (16.5 $miles^2$) with 1,500 element blocks in a relatively coarse grid with block size ranging from 100 to 200 m. The model contains 25 hydrogeologically defined layers, resulting in 39,000 element blocks in the effective-continuum (which represents flow through both fractures and matrix) formulation (Bodvarsson et al. 1997, Chapters 3, 4, 12, 19). Some of the thicker model layers were subdivided into additional grid layers to facilitate numerical resolution. Matrix property data (Flint 1998) used in the unsaturated zone model represent the important variations between hydrogeologic layers at Yucca Mountain. They indicate low matrix permeabilities (on the order of microdarcies) in the welded units (Tiva Canyon and Topopah Spring) and much higher matrix permeabilities (hundreds of millidarcies) in the nonwelded units (Paintbrush and Calico Hills) (Bodvarsson et al. 1997, Chapter 6). A detailed fracture-property model also was developed (Bodvarsson et al. 1997, Chapter 7), using fracture frequency and permeability data from boreholes and the Exploratory Studies Facility, and in situ pneumatic monitoring. Fault properties data, derived primarily from pneumatic monitoring, show that faults have gas permeabilities on the order of hundreds of darcies and that permeability within fault zones has significant lateral variation.

The unsaturated zone site-scale flow model was formulated for both effective-continuum and dual-permeability simulations (Bodvarsson et al. 1997, Chapters 5, 12, and 19). The dual-permeability formulation allows flow to occur either through the matrix or through fractures, and it also allows fracture-matrix interaction. Although studies have demonstrated that the effective-continuum formulation accurately describes fracture-matrix flow for steady-state moisture, heat flow and transient gas flow, the dual-permeability formulation is more rigorous for some unsaturated zone flow problems at Yucca Mountain. Such problems include the simulation of perched water beneath the potential repository (Bodvarsson et al. 1997, Chapter 19) and fracture flow into drifts (Bodvarsson et al. 1997, Chapter 12).

For both model formulations, the upper boundary condition for the flow model was specified as the spatially variable, steady-state net infiltration for present-day climate (Flint et al. 1996). As shown in Figure 2-16, net infiltration ranges from 0.0 to approximately 40 mm (0 to 1.6 in.) per year at Yucca Mountain and is as high as 20 mm (0.8 in.) per year along the crest of Yucca Mountain. Over the spatial extent of the unsaturated zone site-scale model, net infiltration averages 4.9 mm (0.2 in.) per year; over the potential repository area, it averages 6.7 mm (0.3 in.) per year. The infiltration map indicates that most of the infiltration occurs in side slopes and ridgetops where there is minimal alluvial cover.

**Model Calibration.** Initial calibration exercises included matching saturation and water potential data, gas pressures and gas flow rates, ambient temperature and heat flow data, locations and hydrochemistry of perched water bodies, and environmental isotope concentrations and water ages (Bodvarsson and Bandurraga 1996). In addition to model calibration, scientists devoted considerable effort to parameter uncertainties and sensitivity studies for fracture and matrix properties, infiltration patterns, fault properties, and percolation fluxes. Recently, more intensive calibration of the model, with respect to matrix and fracture properties, was achieved through inverse modeling (Bodvarsson et al. 1997, Chapter 6). In this process, a number of one-dimensional submodels were extracted from the full three-dimensional model, corresponding to the locations of the boreholes used in the moisture-flow calibration. The submodels were used, in conjunction with measured saturation and water potential data, to estimate the hydrologic properties of the matrix rock in each layer. The hydraulic properties of the fractures were then estimated by comparison to measured borehole pneumatic-pressure records. In addition, layer-averaged values for the rock matrix and the fracture network were developed from the set of properties chosen from the individual inversions. To account for the fraction of the fracture plane actually being occupied by water the surface area available for fracture-to-matrix flow was taken to be the nominal fracture-matrix interface area (as estimated by fracture spacing data) multiplied by the liquid saturation in the fracture.

**Percolation Flux at the Potential Repository Horizon.** Modeled percolation flux in the potential repository horizon is approximately 1–10 mm (0.04–0.4 in.) per year, which is consistent with infiltration estimates by Flint et al. (1996) and estimates of percolation flux from borehole temperature analyses (Bodvarsson and Bandurraga 1996). Those results were based on using the spatially variable infiltration rates at the ground surface as a boundary condition and calculating the flux magnitudes entering the potential repository horizon from the simulation results. Further attempts to constrain estimates of percolation flux at the potential repository horizon involved additional analysis of borehole temperature data (Bodvarsson et al. 1997, Chapter 11) and geochemical data (Bodvarsson et al. 1997, Chapters 14-18). A study involving numerical model analysis of chloride concentrations in precipitation, and in pore water and perched water in the unsaturated zone, concluded that the estimated mean infiltration rate for the unsaturated zone site-scale model area, 4.9 mm (0.2 in.) per year, probably is a maximum value for the potential repository at Yucca Mountain under present-day climate (Bodvarsson et al. 1997, Chapter 15). Depending on the total chloride flux at the surface, the mean infiltration may be as low as 1 mm (0.04 in.) per year. Analyses of strontium and carbon-14 data from selected boreholes also are consistent with a percolation flux in the range of 1 to 10 mm (0.04 to 0.4 in.) per year (Bodvarsson et al. 1997, Chapters 17, 18).

Figure 2-17 shows total percolation flux at the potential repository horizon, as simulated by the unsaturated zone site-scale flow model for present-day climatic conditions, using the dual-permeability formulation and the base case parameter set (Bodvarsson et al. 1997, Chapter 22). Within the model area, percolation flux ranges from 0.0 to about 40 mm (1.6 in.) per year, and up to about 20 mm (0.8 in.) per year, within the potential repository area. The heterogeneity in percolation flux is generally similar to the variability in infiltration. However, the spatial grid for the unsaturated zone model is coarser (100 to 200 m grid blocks) than the 30 m grid block size of the infiltration model. Because the unsaturated zone model averages the inputs from the more spatially detailed infiltration model, calculated percolation fluxes may not reflect the extent of variability associated with the infiltration model results.

The spatial heterogeneity of percolation flux is also dependent on variations in hydrologic properties (especially fracture distribution and characteristics) that occur on a finer scale than individual grid blocks. Based on observations of fractures and fracture fillings, it is likely that flow in fractures is variable at a scale of meters to tens of meters (i.e., all or most of the flow within a given grid block may occur within a finite and small number of fractures). Because of the uncertainty regarding the number and location of specific flow paths, the estimates of effective porosity used by the model are also subject to significant uncertainty; local areas of higher fracture porosity than are currently reflected in the model may be present. Because of the inherent difficulty in characterizing the spatial variability in hydrologic properties, the model incorporates a probabilistic distribution of property values.

Although this distribution of percolation at the potential repository horizon is similar to the distribution of net infiltration (Figure 2-16), some notable differences do exist. For example, in the percolation-flux distribution, flux is greater than 10 mm (0.4 in.) per year over approximately 10 percent of the potential repository area. In the infiltration distribution, infiltration is greater than 10 mm (0.4 in.) per year over 25 percent of the potential repository area (Bodvarsson et al. 1997, Chapter 20). In this analysis, the fact that infiltration at the land surface is greater than percolation at the potential repository horizon suggests that a relatively small amount of lateral flow occurs in the Paintbrush nonwelded unit above the potential repository area. In this simulation, 80 percent of the percolation flux at the potential repository horizon occurs as fracture flow (Bodvarsson et al. 1997, Chapter 21).

To bound possible values of percolation flux at the potential repository horizon, various model simulations were conducted using multiples of the estimated net infiltration rate. These simulations indicate that percolation flux values exceeding 20 mm (0.8 in.) per year are inconsistent with measured temperature and chloride concentrations; it would be difficult to obtain a calibrated model with higher flux. This suggests that actual percolation flux values are most likely less than 20 mm (0.8 in.) per year (Bodvarsson et al. 1997, Chapter 20). The lower limit of percolation flux could be close to zero but is more likely on the order of 0.5 mm (0.02 in.) per year.

**Seepage Into Potential Repository Drifts.** Seepage into the emplacement drifts has been estimated from detailed simulations of the flow near the drifts (Tsang et al. 1997). These simulations have used representations for the spatial variability in both flow properties and the percolation flux and have considered time variation in the percolation. The model has been used to predict seepage in liquid release tests in niches in the Exploratory Studies Facility and found to provide reasonable agreement to the observations (Wang et al. 1998). The three-dimensional model has incorporated the results of these simulations to provide estimates of the seepage that might occur in the repository. To obtain boundary conditions, a detailed, north-south, two-dimensional, cross-sectional model through the potential repository area was developed that explicitly accounts for each drift (Bodvarsson et al. 1997, Chapter 4). The detailed model simulations estimate the spatial variability in percolation flux at the potential repository horizon (0–20 mm, or 0–0.8 in. per year) that is consistent with that from the site-scale, three-dimensional unsaturated zone model (Bodvarsson et al. 1997, Chapter 12). These simulations predict that percolation flux would be 10 mm (0.4 in.) per year or greater over approximately 25 percent of the potential repository drifts. Modeling results also show that the dual-permeability and effective-continuum formulations of the detailed model calculate nearly identical distributions of percolation flux for steady-state flow.

Although the seepage model considers the spatial heterogeneity of percolation, the model probably does not reflect the full range of local variability. Because the relatively coarse grids (100–200 m) (328–656 ft) used by the unsaturated zone model result in the averaging of infiltration fluxes over larger areas, the model may not reproduce potential local zones of high percolation flux and seepage at a drift scale. In addition, because the distribution of fracture flow paths is heterogeneous, the model does not simulate high fluxes that may occur in very spatially restricted pathways. Even though the average percolation flux may range from 0 to 20 mm (0 to 0.8 in.) over a scale of tens of meters, local fluxes at the centimeter scale of individual fractures could be many times the average values. Finally, current models do not consider the effects of drift geometry or characteristics (e.g., wall roughness) on seepage. All of these uncertain factors regarding seepage are relevant to the potential for percolating water to contact waste packages and transport radionuclides: however, their significance to performance calculations has not been fully assessed.

**Flow Below the Potential Repository.** Spatial distributions of perched water below the potential repository area were successfully reproduced by simulations using the three-dimensional, site-scale unsaturated zone model (Bodvarsson et al. 1997, Chapters 13, 22). The simulations were successful in the northern part of the potential repository area where the Topopah Spring welded unit basal vitrophyre is the perching layer, and in the southern part where the deeper vitric-zeolitic boundary in the Calico Hills nonwelded unit is the perching layer. Transport simulations imply that it would take approximately 7,500 years for a particle of water to travel from the land surface to the approximate location of the perched water in the northern part of the area, mostly in the Paintbrush nonwelded unit. Model results indicate that flow below the potential repository, which encounters a generally eastward-dipping perching layer, will be diverted laterally. Lateral flow is expected to continue until reaching the water table or until encountering a fault or extensive fracture system that can reinitiate downward vertical flow (Bodvarsson et al. 1997, Chapter 22). For zeolitic layers that do not cause significant perching or diversion, percolation fluxes higher than several millimeters per year must occur as fracture flow because matrix permeabilities are relatively small. The relatively fast fracture flow would result in reduced contact time with the sorptive zeolites.

In the southern part of the potential repository, a significant portion of the Calico Hills formation is vitric with relatively high fracture permeability. Flow below the potential repository in this area likely will travel vertically until the lower altered portion of the Prow Pass formation is encountered near the water table. It is uncertain how much of the water that percolates from the potential repository region to the water table would pass through the sorptive zeolites in the Calico Hills formation as matrix flow. This uncertainty is caused by potential fracture flow and lateral diversion, but the amount is probably a small part of the total flow. Overall, model results indicate that 40 percent of the percolation flux that reaches the water table beneath the potential repository area is fracture flow.

**Impact of Future Climate-Change Scenarios on Unsaturated Zone Flow Model Results.** The three-dimensional, site-scale unsaturated zone flow model was used to examine the effects of increased infiltration on the unsaturated flow system. The model used a range of assumptions to test the effects of future climate change on the nature and rate of flow. The climate change scenarios considered included an increased carbon dioxide "greenhouse" scenario, and the onset of pluvial conditions similar to those that existed during the glacial maximum of 21,000 years ago (Bodvarsson et al. 1997, Chapter 23). For the greenhouse scenario, net infiltration rates at the land surface were increased by a factor of two relative to present-day net infiltration, which averages approximately 4.9 mm (0.2 in.) per year over the area of the unsaturated zone model. For the pluvial scenario, net infiltration rates were increased by a factor approximately five times that of the present day. Estimates of travel time for a single particle from the land surface to the perched water body in the northern part of the area decreased to about 3,000 years in the greenhouse scenario and to less than 1,500 years in the pluvial scenario.

Simulation results for possible wetter future climates also show a decrease in the lateral diversion of water along the Paintbrush nonwelded unit (represented without fractures) and an increase in the lateral diversion along the Calico Hills nonwelded unit zeolitic interface. The decrease in lateral diversion along the Paintbrush nonwelded unit occurs because the relative permeability increases as the saturation increases, decreasing the capillary barrier effect, and thereby reducing this layer's capability to divert moisture. The Calico Hills nonwelded unit zeolitic horizon, however, has a very low permeability. As a result, increased saturation forces the water to be laterally diverted. Fracture flow is expected to be the dominant flow mechanism affecting moisture distribution at the potential repository horizon because of the low matrix permeabilities within the Topopah Spring welded unit. Percolation flux is significant in the northwest portion of the model domain where infiltration is relatively large and lateral flow is blocked by the Solitario Canyon fault. Drill Hole Wash, Sever Wash, and Pagany Wash faults are also associated with high percolation fluxes at the water table. The wetter climate simulations project increases in the elevation of perched water of 0.1-7.9 m (0.3-26 ft). Modeling results address the NRC subissue on the spatial distribution of groundwater percolation through the proposed repository horizon during the period of repository performance. This subissue is part of the Key Technical Issue on Unsaturated and Saturated Flow Under Isothermal Conditions (NRC 1997a) (see Volume 4, Section 4.3.3.9).

### 2.2.3.3 Status of Unsaturated Zone Studies

Scientists to date have provided a model of infiltration at Yucca Mountain, characterized the hydrologic properties of the geologic units making up the mountain, evaluated the partition of flow between fractures and rock matrix for different geologic units, and developed a three-dimensional model of how water moves from the surface to the water table. Future work will address remaining information needs including the effects of ventilation on moisture within the mountain. Future studies will also capitalize on the excavation of the cross-drift to better define the past distribution of water movement in the unsaturated zone and to test the models that have been developed for unsaturated zone flow and seepage into drifts.

### 2.2.4 Water Below the Water Table (Saturated Zone Hydrology)

Any releases from the proposed repository would eventually migrate downward through the unsaturated zone to the water table and travel to the accessible environment. Therefore, understanding the flow and transport of radionuclides through the saturated zone is an important component of the overall assessment of potential repository performance. The water table near the repository is currently at an elevation of approximately 730 m (2,395 ft), more than 300 m (984 ft) below the proposed repository horizon. Within the saturated zone, water movement is a function of the fracture and matrix hydraulic properties of the saturated volcanic units below the repository and of the other hydrologic units through which the water would eventually travel.

The systematic description of the regional hydrogeologic framework and regional flow modeling (D'Agnese et al. 1997a; 1997b) forms the context for characterizing the saturated zone hydrology of the proposed repository site. Figure 2-18 is a schematic north-south cross section showing the important components of the saturated zone flow system at a regional scale. Water infiltrating the unsaturated zone becomes recharged to the regional flow system. Water moves generally southeast beneath the site before flowing south out of the volcanic rocks and into the thick valley fill of the Amargosa Desert. Figure 2-19 shows the elevation of the water table throughout the region from north of the site, where most local recharge occurs, to Amargosa Valley.

Information on the saturated zone near Yucca Mountain addresses the NRC Key Technical Issue on Unsaturated and Saturated Flow Under Isother-

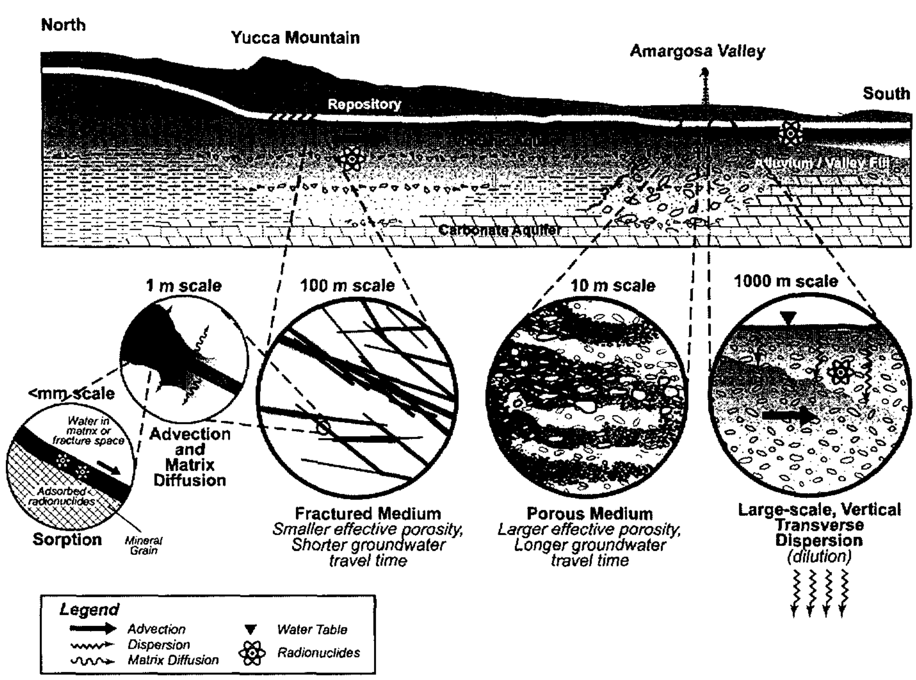


Figure 2-18. Cross Section Showing Conceptual Model of the Saturated Zone Flow System from Yucca Mountain to Amargosa Valley

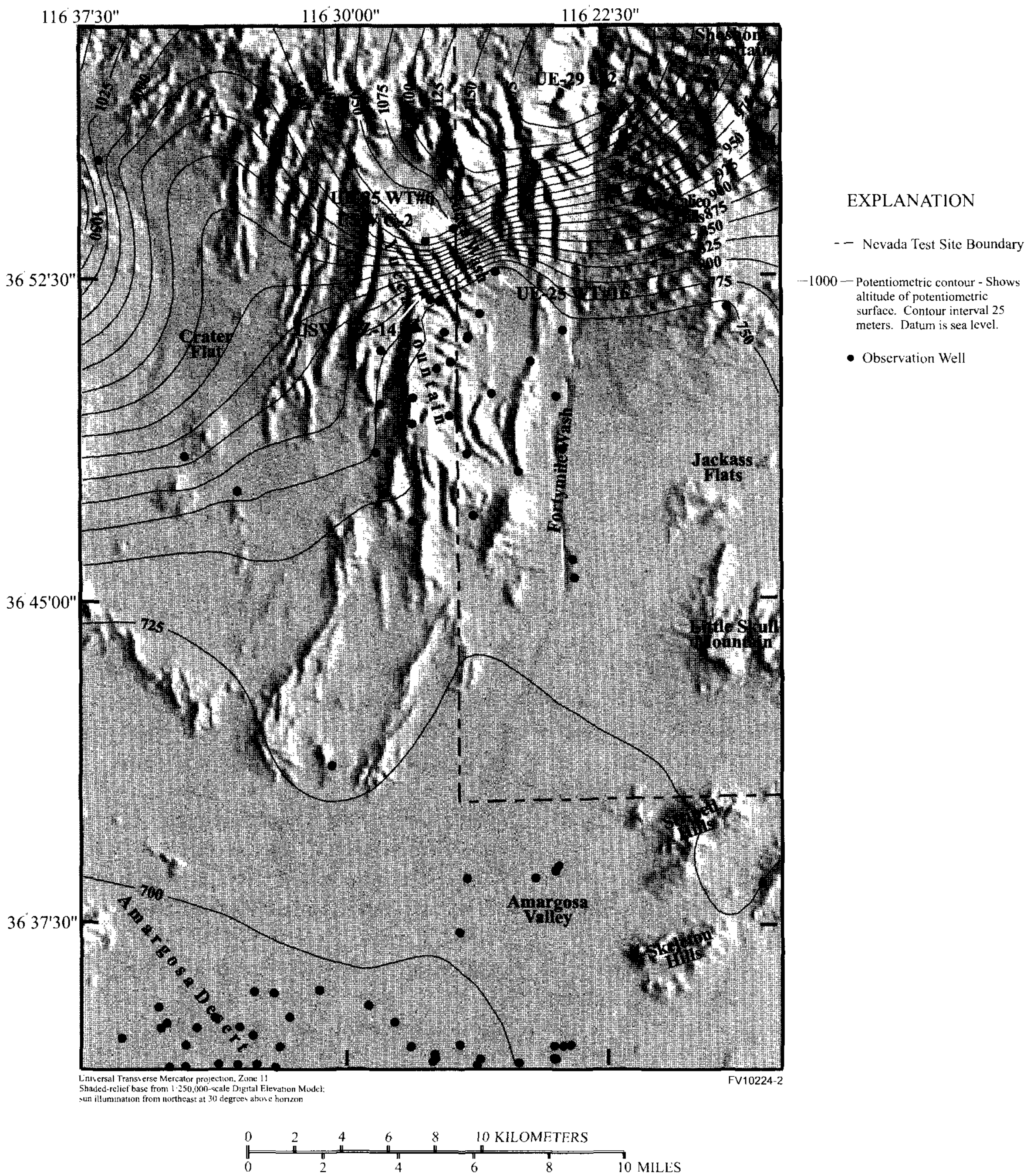


Figure 2-19. Potentiometric Surface (Water Table Elevation) in the Yucca Mountain Region

mal Conditions (NRC 1997a). In addition, it helps to answer questions related to the issues of Total System Performance Assessments and Integration and Activities Related to Development of the U.S. Environmental Protection Agency Yucca Mountain Standard (NRC 1997a). These issues are discussed in more detail in Volume 4, Section 4.3.3.

#### 2.2.4.1 Regional Hydrogeology

Yucca Mountain lies within the Alkali Flat-Furnace Creek groundwater subbasin, one of several that comprise the Death Valley regional flow system (D'Agnese et al. 1997a). Groundwater in the Alkali Flat-Furnace Creek subbasin, together with that flowing in the Ash Meadows subbasin to the east and the Oasis Valley subbasin to the west, discharges to the surface primarily in the Amargosa Desert south of Yucca Mountain. Part of the flow may continue to Death Valley either by deep westward underflow in a regional carbonate aquifer or by seepage from the basin-fill sediments through the bordering mountain ranges to Death Valley. Recharge (rainfall that enters the flow system) to the northeastern quadrant of the Death Valley system occurs principally at higher elevations such as the Spring Mountains, the Sheep Range, Rainier Mesa, Pahute Mesa, and Timber Mountain. The area north of Yucca Mountain, including Central Pahute Mesa, Timber Mountain, and Shoshone Mountain provides most of the recharge to the Alkali Flat-Furnace Creek subbasin. Most discharge occurs by evaporation and plant transpiration in the Amargosa Desert.

Near Yucca Mountain, volcanic rocks up to several thousand meters (more than 6,000 ft) thick cover the Paleozoic and older rocks in the region. As described above, they have hydrologic properties that change dramatically over short distances, both laterally and vertically, producing a complex hydrogeology. The volcanic rock section becomes thinner to the south and is not an important component of the saturated zone flow system in southern Amargosa Valley.

The dominant regional aquifer, the carbonate aquifer, consists of Paleozoic marine limestones, dolomites, and minor clastic (made up of fragments) sediments that attain a thickness of thousands of meters. Fractures enlarged by dissolution provide the large permeability associated with this aquifer, which underlies most of the Ash Meadows subbasin and the southern part of the Alkali Flat-Furnace Creek subbasin. Although the Paleozoic stratigraphic section is segmented and disrupted by complex faulting and volcanic activity in the region, the carbonate aquifer connects and hydrologically integrates the many valleys and intervening ranges. Beneath the carbonate aquifer are relatively impermeable, metamorphosed older rocks, known as the lower clastic aquitard or the Paleozoic-Precambrian clastic confining units (D'Agnese et al. 1997a, p. 20). These rocks form the effective hydraulic basement for groundwater flow, but they are locally permeable where they contain unhealed fractures. In the vicinity of Yucca Mountain, the carbonate aquifer is not currently tapped as a source of groundwater because of its great depth below the surface.

Faulting and fracturing of bedrock is also important to the regional hydrologic flow system (Faunt 1997). In the Yucca Mountain region, north to northeast-striking faults are more likely than those of other orientations to be permeable, because they are approximately perpendicular to the least principal stress. Furthermore, they are oriented favorably to transport water from the highlands in the north to areas of discharge in the lower basins in the south and southwest.

Within the volcanic rock section, alteration (e.g., the formation of zeolite minerals in some tuff units) is more extensive at depth, which may diminish rock permeability. Therefore, the deeper volcanic rocks tend to impede flow and confine the underlying Paleozoic carbonate aquifer.

Structural basins (valleys) formed during Mid-Tertiary crustal extension near Yucca Mountain are filled with gravel, sand, silt, and clay eroded from the adjacent uplands. Some spring deposits, fresh-water limestone (lake deposits), and basaltic lava flows also occur. The Quaternary-Tertiary valley-fill deposits constitute a major aquifer hundreds of meters thick, though of widely variable properties, in the Amargosa Desert and other deep basins of the region (D'Agnese et al. 1997a, pp.

17–19). They probably are hydrologically important also in southern Crater Flat and in southwestern Jackass Flats, where significant saturated thicknesses are likely but have not been confirmed by drilling.

### 2.2.4.2 Site-Scale Hydrologic Setting

Results of saturated zone hydrologic investigations at and near Yucca Mountain have been summarized (Luckey et al. 1996). Except for one borehole, the drilling program has not reached the base of the Tertiary volcanic section. North of the proposed repository, the volcanic rocks are at least 1,829 m (6,000 ft) thick. Near the southern boundary, drilling has established a minimum depth of 1,533 m (5,029 ft). Based on rock type and flow properties, Luckey et al. (1996) have divided the volcanic rocks below the water table into four hydrogeologic units. These are known from the top down as the upper volcanic aquifer, the upper volcanic confining unit, the lower volcanic aquifer, and the lower volcanic confining unit. The upper volcanic aquifer is composed of the Topopah Spring welded tuff, which occurs in the unsaturated zone near the repository but is present beneath the water table to the east and south of the proposed repository and in Crater Flat. The upper volcanic confining unit includes the Calico Hills nonwelded unit and the uppermost, unfractured part of the Prow Pass tuff where they are saturated. The lower volcanic aquifer includes most of the Crater Flat Group (Luckey et al. 1996, pp. 18–20), and the lower volcanic confining unit includes the lowermost Crater Flat Group and deeper tuffs, lavas, and flow breccias. The upper volcanic aquifer underlying Yucca Mountain is generally productive and provides a source of groundwater for the site.

The main distinction between saturated zone volcanic aquifers and confining units is that the aquifers tend to be more welded and contain more permeable fractures. However, alteration of the tuffs to zeolites and clays, which reduces permeability, is more pronounced at depth, and the greater pressure tends to reduce fracture permeability. Consequently, a combination of factors including fracture properties, mineralogy, and depth, rather than just rock type, determines the hydrologic character of the volcanic rocks below the water table at Yucca Mountain.

Hydraulic tests have been performed to determine the properties of the saturated zone units. The analyses are limited by significant uncertainties about the extent to which fractures affect the unit conductivity (a measure of the ability of the rocks to transmit flow) (Luckey et al. 1996, pp. 32–36). However, ranges of values of conductivity are reported to provide comparison among the units. The confining units had low conductivities that ranged from 0.000005 m to a maximum of 0.26 m (0.00002 to 0.85 ft.) per day, whereas, the aquifers had moderate to high conductivities ranging from 0.00004 m to 18 m (0.0001 to 59 ft.) per day. Intervals without open fractures in all units tend to have very low hydraulic conductivity reflecting the conductivity of the rock matrix or of very small fractures (Luckey et al. 1996, p. 32). Conversely, larger values of apparent hydraulic conductivity for both aquifers and confining units can generally be attributed to fractures.

Hydraulic tests at Yucca Mountain were performed in both single-borehole and multiple-borehole tests. Transmissivities (another measure of the rock's ability to transmit water flow) measured in the multiwell tests tend to be approximately two orders of magnitude (100 times) greater than those determined from single-borehole tests in the same borehole. This observation suggests that the multiwell tests, which sample larger rock volumes, are also encountering a larger number of permeable fractures (Luckey et al. 1996, p. 36). The test results also support the hypothesis that fractures are more important than rock type in controlling saturated hydraulic conductivity of the volcanic rocks.

The chemistry of saturated zone waters beneath Yucca Mountain (Oliver and Root 1997) reflects processes that impacted these waters as they flowed to the Yucca Mountain area from recharge areas to the north (McKinley et al. 1991). In general, they are dilute sodium-bicarbonate waters that are neutral to mildly alkaline and mildly oxidizing. Similarities between the composition of saturated zone waters in the recharge areas and Yucca Mountain suggest that water compositions primarily reflect water-rock reactions in the recharge areas. Because flow paths from the recharge areas through the Yucca Mountain area are largely through similar volcanic rocks, water compositions do not change greatly as they flow through the system although there are exceptions to this general statement. The concentration of some dissolved species, such as metals, can be altered through reactions with clays and zeolites. Variations in acidity and oxidation state can result from changes in gas compositions (e.g., dissolved carbon dioxide, dissolved oxygen and methane). Various processes including gas sources at depth, the presence of reactive minerals, or microbial activity may change gas compositions. Processes controlling saturated zone water compositions are sufficiently well known that bounds can be placed on the expected range of future compositions.

#### 2.2.4.3 Flow Paths

Regional water level contours (Figure 2-19) show a southward slope of the water table from recharge areas in the northern part of the Alkali Flat-Furnace Creek subbasin toward discharge areas in the southern Amargosa Desert. The Yucca Mountain site occupies an intermediate position along this path in an area where the contours indicate a probable southeastward flow direction. Water flowing beneath Yucca Mountain arrives from the north and west. North-south and northwest-southeast oriented faults and fractures probably assert a strong influence on flow direction and contribute to continued southerly flow. East and southeast of the site, the upper volcanic aquifer is below the water table adjacent to north-south faults, which may enhance southward flow but impede eastward flow. South of the site, the Spotted Range-Mine Mountain fault zone (Faunt 1997, pp. 26–27) crosses the projected flow path from the repository and may create pathways for southwestward flow.

The site is just south of a zone in which there is a large hydraulic gradient (slope in the water level elevations) toward the south. Similar gradients elsewhere in the Death Valley groundwater basin are generally associated with flow through the Paleozoic-Precambrian clastic confining unit or the Eleana Formation, an argillite (claystone) that interrupts the regional Paleozoic carbonate aquifer in the Nevada Test Site area (Winograd and Thordarson 1975, pp. C63–C69). The cause of the gradient north of Yucca Mountain is not known with certainty, but several hypotheses have been proposed.

The higher water levels in the north, which occur in the upper volcanic aquifer, may be hydraulically decoupled, by the thick upper volcanic confining unit, from the water levels measured south of the gradient, which occur in the lower volcanic aquifer, a condition known as semiperched. Alternatively, the water table to the north may be a perched, saturated zone above rocks that are unsaturated and overlie the regional water table. Both explanations are consistent with known geologic and hydrologic data and imply that conditions at Yucca Mountain are different from, and independent of, conditions in the deep carbonate aquifer and lower volcanic confining units. If the area of the large hydraulic gradient is decoupled from or perched above the regional flow system, it may be that regional flow from north to south is diverted to more permeable pathways, possibly westward to Crater Flat or eastward to the Fortymile Wash area.

Along the projected flow path from the Yucca Mountain site to the Amargosa Desert, the Tertiary volcanic rocks thin from about 2,000 m (6,562 ft) at the site to tens of meters or 0 m (0 ft) because of distance from their source and erosion. As shown on Figure 2-18, they are covered by the Quaternary-Tertiary valley-fill aquifer (D'Agnese et al. 1997a, p. 17). Paleozoic and older rocks, which are deeply buried near the site, occur at shallow depths and are locally exposed in hills at the northern edge of the Amargosa Desert. The Paleozoic and older rocks also are mainly covered by the Amargosa valley-fill aquifer. After entering the valley-fill aquifer, flow generally continues southerly past the town of Amargosa Valley and toward the Amargosa Farms area (Figure 2-19). Here, the valley-fill aquifer has thickened to at least several hundred meters. Data are not sufficiently detailed to permit precise predictions of flow paths in this area, and the local flow paths may be complicated by inflow from the regional carbonate aquifer, and by withdrawal of water in large irrigation wells. Because of the high aquifer permeability, it is likely that the cone of depression associated with extensive pumping for irrigation would capture most flow from the north.

Borehole measurements in volcanic rocks near Yucca Mountain reveal small amounts of flow, some downward and some upward, in saturated zone volcanic units. However, in a well approximately a mile east of Yucca Mountain that penetrated the deep, faulted contact between volcanic rocks and the regional carbonate aquifer, there was significant and persistent upward flow from the deep carbonate rocks into the volcanic rocks. An abrupt increase in hydraulic head (or water pressure) of 20 m (66 ft) occurred when the fault zone was penetrated, and the higher head persisted in the deeper carbonate aquifer. Higher heads with increased depths, which indicate the potential for upward flow, have been observed in other deep holes that penetrate the lower volcanic confining unit. Luckey et al. (1996, pp. 27–29), therefore, inferred that upward water pressure, presumably from the carbonate aquifer, was reflected in the higher heads measured in deep volcanic rocks. The significance of this observation is that water (and radionuclides) within the volcanic rocks would not enter the regional carbonate aquifer.

The geothermal gradient is variable over the Yucca Mountain site, which suggests that shallow processes, such as groundwater flow, may influence the thermal regime. Heat flow is low for the Yucca Mountain area, probably because groundwater flow beneath the volcanic rocks (in the carbonate aquifer) is intercepting the heat and transporting it elsewhere (Sass et al. 1995, p. 165). Detailed water temperature measurements suggest that faults may provide steep tabular zones of higher permeability that allow some upward flow of water and thermal energy (Sass et al. 1995, p. 166; Bredehoeft 1997, p. 2463). This interpretation is consistent with the upward gradients observed in boreholes, and it also supports the hypothesis that faults are important regional flow paths.

#### 2.2.4.4 Saturated Zone Flow Modeling

Analyses of groundwater flow and radionuclide transport in the saturated zone use numerical modeling results at different scales for site characterization and performance assessment calculations. D'Agnese et al. (1997a) developed a regional-scale flow model that encompasses a large portion of southern Nevada and parts of eastern California. The model design incorporates natural system boundaries and conditions (e.g., contacts between alluvium, volcanic rocks and carbonate rock, and the expected locations of recharge and discharge) to constrain groundwater flux estimates. The estimate of groundwater flux through the saturated zone flow system is based on the system's overall water budget. The regional-scale model has also been used to estimate the influence of climate change on groundwater flux and flow direction (D'Agnese et al. 1997b).

The saturated zone numerical flow model used to assess the performance of the repository is described in Section 3.7 of Volume 3. The model is coupled to the unsaturated zone flow and transport model (Section 2.2.5 of this volume), and utilizes a stream tube approach to represent flow from below the repository to the accessible environment in Amargosa Valley. Flow and transport are modeled as six flow tubes corresponding to the subregions defined for the unsaturated zone. Transport processes such as dispersion, dilution and sorption, and hydrologic pathways and properties are modeled for each flow tube.

The saturated zone flow and transport models are subject to substantial uncertainty as a result of the scale of the model, which extends over more than 20 km downgradient, and from the surface to depths of several kilometers. Most of the current saturated zone data has been collected near the repository: however, even with a great deal more data than is presently available, it would not be possible to define flow direction or transport properties along the entire path length. Thus, there is large uncertainty in the model representation of flow directions, flux rates, geochemical conditions and transport properties such as sorption and precipitation. Because of the scale effects, it is difficult to compare the stream tube modeling approach to other conceptual models, or to assess whether alternative methods might be more or less appropriate.

#### 2.2.4.5 Stability of the Water Table

After recovery from drilling disturbances, water levels measured in wells have remained stable during site characterization monitoring at Yucca Mountain. Small, temporary changes result from earth tides, barometric changes, and crustal strain related to earthquakes. Mineralogical studies of minerals deposited by water in the past (Levy 1991; Chipera et al. 1995) suggest that past maximum water levels have been no more than approximately 60 to 130 m (197 to 426 ft) higher than the present. This estimate is similar to and consistent with a modeling simulation of the effects of the glacial maximum 21,000 years ago, which predict a 60 to 150 m (197 to 492 ft) rise at Yucca Mountain (D'Agnese et al. 1997b).

#### 2.2.4.6 Status of Saturated Zone Studies

Scientists studying the saturated zone have defined the current elevation of the water table near Yucca Mountain and have gathered information indicating its level under past wetter conditions. They also have characterized the flow properties of hydrogeologic units found in the saturated zone near the site. A regional model of saturated zone flow provides a framework for the site model. These results all address the NRC subissue on ambient flow conditions in the saturated zone, which is part of the Key Technical Issue on Unsaturated and Saturated Flow Under Isothermal Conditions (NRC 1997a). Future work to address information needs will focus on refining the interface between the regional and site models, completing the characterization of hydraulic parameters, and establishing a series of monitoring wells south of the site to define the interactions between the volcanic aquifer and the underlying carbonate aquifer.

### 2.2.5 Factors Affecting Radionuclide Transport

The chemistry of rocks and fluids, and the type and distribution of minerals present, can directly affect the potential movement of water and radionuclides toward the accessible environment. The chemical environment (temperature, pH, Eh) surrounding waste packages and waste materials will directly influence the rates of waste package corrosion and waste dissolution, as well as radionuclide concentrations in water. Minerals precipitated in fractures can significantly affect flow paths by altering rock mass permeability. Also, some minerals can retard the migration of certain species, such as radionuclides, dissolved in water. By a process known as sorption, radionuclides can bind to mineral surfaces. Retardation of dissolved or colloidal species can also occur. Through a process known as matrix diffusion, water and dissolved constituents can migrate from fractures into the rock matrix where they move more slowly. Dispersion (the process of dissolved species spreading out during mixing with other groundwater) and dilution can decrease the concentration of constituents contained in the water. The characteristics of the rock mass that control the flow of groundwater and its constituents are known as transport properties.

In addition to affecting transport properties, mineralogy and geochemical composition reveal the history and evolution of rock units. The minerals that comprise the rock mass and are found along fractures reflect past conditions in the hydrogeologic system and provide evidence of the nature and extent of water flow. The past history of water determines its chemistry and provides clues of how the hydrologic system might behave in the future. Geochemical information also indicates the age of water at Yucca Mountain and the paths by which it has flowed in the past.

Results of transport and other geochemical investigations allow several of the NRC key technical issues to be addressed, most directly the issue of Radionuclide Transport (NRC 1997a). The results also will provide information addressing the issues of Unsaturated and Saturated Flow Under Isothermal Conditions and Total System Performance Assessment and Integration. The NRC key technical issues are discussed in more detail in Volume 4, Section 4.3.3.

#### 2.2.5.1 Overview of Transport Processes and Models

Figure 2-20 schematically depicts the important properties and processes that may affect radionuclide transport in the unsaturated and saturated

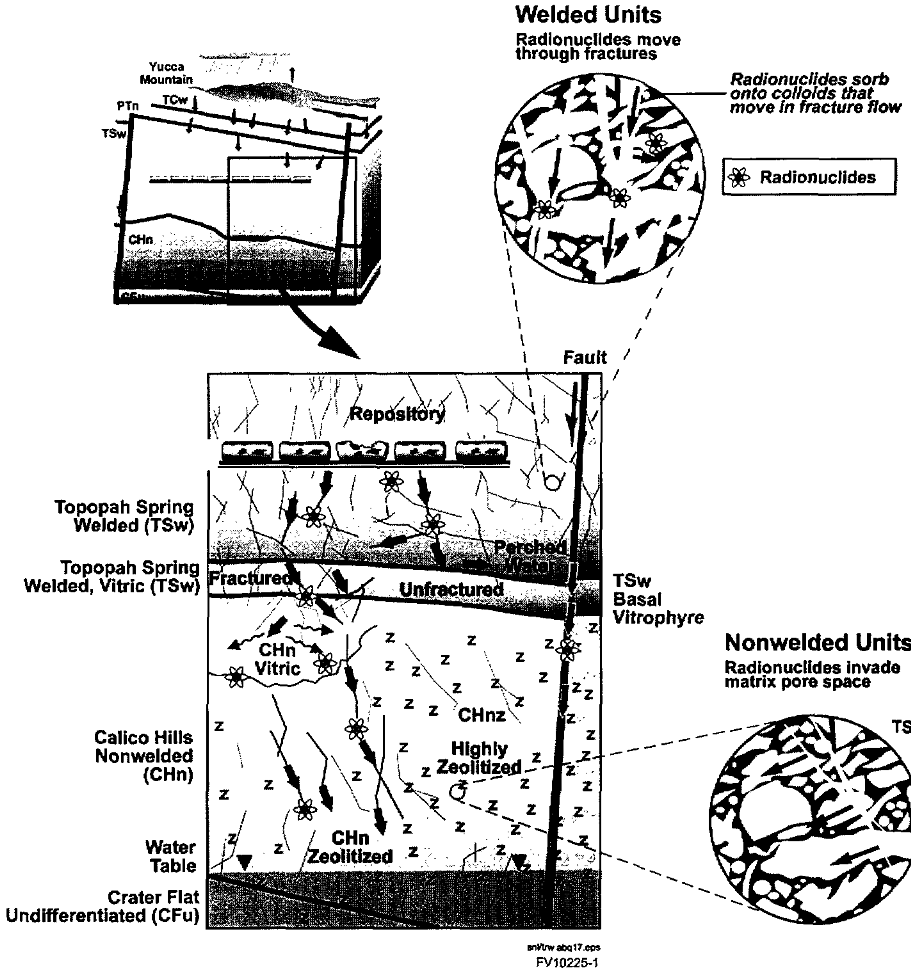


Figure 2-20. Schematic Cross Section of the Yucca Mountain Site Showing Conceptual Unsaturated Zone Transport Processes

zones at Yucca Mountain. As the figure shows, percolating water that could penetrate a waste package and contact waste materials may acquire and transport radionuclides either in suspension, bound to very small particles known as colloids, or in solution (i.e., as a dissolved solid). Colloid particles are small enough to travel with flowing water through the fractures and matrix of the rock, and certain colloids also have the ability to bind radionuclides to their surfaces. After release from the waste package, fluids will migrate downward through the near-field repository environment and through any natural or engineered materials (like backfill or concrete) that may be present at the base of the repository drift. Because the transport of radionuclides and other species (either in solution or bound to colloids) is highly dependent on geochemical conditions, a challenge for transport models is to assess the effect that the near-field environment has on fluid chemistry. Some materials may have the ability to significantly alter chemical conditions, thereby changing the ability of the fluids to transport constituents.

After moving through the near-field, percolating water would enter the host rock, welded Topopah Springs tuff, which would likely have been altered by repository-induced heat and fluid flow. Based on the information presented in Section 2.2.3, water would primarily flow through rock fractures. Transport of dissolved or colloidal species would depend on several factors: geochemical conditions in the fractures (pH, Eh, temperature, etc.); the type and distribution of minerals present on the walls of the fractures, especially those that sorb radionuclides; and the nature and extent of interaction between fractures and matrix. Interaction between fractures and matrix may enhance retardation by allowing radionuclides to migrate into the matrix and become bound to matrix minerals or trapped in pores.

Water continuing downward beneath the repository would encounter significantly different hydrologic conditions and flow properties upon contacting the Calico Hills nonwelded unit. Conditions in the Calico Hills unit are likely to be variable across the repository, so the relevant transport processes also may vary. In many areas, it is expected that flow would be primarily in the matrix and that percolating water would contact both vitric and zeolitic tuffs. The zeolitic units would probably retard migration of strongly sorbing radionuclides in these regions. In other areas, perched water zones resulting from low matrix permeabilities or hydrologic discontinuities may result in lateral diversion. Depending on the extent of the perched zone, water may either be laterally diverted for short distances before returning to the unsaturated zone or continue laterally to the water table, bypassing the lower unsaturated zone altogether. Finally, flow in some portions of the Calico Hills unit (particularly the vitric tuffs in the southern part of the repository) may occur mainly in fractures, where the effectiveness of retardation processes would depend on the same factors described above.

Major faults or fracture zones may also provide a pathway for rapid vertical flow in any of the hydrologic units. These features could provide a means for collecting and focusing flow from a relatively wide area into narrow zones with correspondingly higher flow rates and velocities.

After reaching the water table, flow will continue downgradient (generally to the southeast) away from the repository. Based on the characteristics of saturated aquifers described in Section 2.2.4, it is likely that the majority of saturated flow would occur in zones with enhanced permeabilities caused by fractures. Retardation processes such as sorption, matrix diffusion, and dispersion would also function in the saturated zone. As in the unsaturated zone, the effectiveness of the retardation processes would depend on the geochemical environment in which water is moving. Therefore, an adequate understanding of the geochemical and transport properties of the rocks is necessary to demonstrate whether the saturated zone can assist in protecting public health and safety.

To support assessments of potential repository performance, transport models for the site-scale unsaturated zone (Robinson et al. 1997) and the regional saturated zone (Zyvoloski et. al. 1997) have been developed to evaluate conceptual models, numerical methods, and parameter sensitivities. Because it is not possible to run field experiments that realistically simulate system behavior over the distances and time frames involved (that is, tens of kilometers and thousands of years), it is difficult to calibrate the models. However, the models have been tested by comparison to the known distribution of environmental isotopes and water chemistry in the unsaturated zone. The studies suggest that under certain conditions, radionuclides could reach the water table within on the order of 100 years or less. Fast transport could occur if continuous fracture pathways through the Calico Hills nonwelded unit are present and percolating water has only limited contact with zeolites. Also, colloid transport of certain radionuclides, such as plutonium, could result in relatively fast transport.

### 2.2.5.2 Geochemistry of the Site and the Surrounding Region

**Geochemical Framework.** As described in Section 2.2.1, Yucca Mountain is composed of a thick series of volcanic rocks overlying Paleozoic sediments. Most of the volcanic section consists of ash flow tuffs up to several hundred meters thick that range from rhyolite to quartz-latite in geochemical composition. Rhyolites have a higher content of silica and alkali elements and a lower percentage of aluminum and metallic elements than quartz-latites. The units found along potential pathways below and away from the repository (and below the water table) are mostly rhyolitic, whereas the horizons above the proposed repository are mostly quartz latite.

The quartz latite units are the source of natural geochemical "tracers" that may aid in understanding transport in the unsaturated zone. The units above the proposed repository consist of porous, vitric (glassy) material in the Pah Canyon unit and underlying bedded tuffs, overlying a dense and relatively impermeable quartz-latite vitrophyre in the upper Topopah Spring tuff. Waters that have reacted with the quartz-latitic glass acquire a unique trace-element signature characterized by enrichment in light lanthanide elements and a diminished or absent europium anomaly. This signature, and its modification with transport, can be traced to depth. For example, the source of the water that precipitated calcite in fractures can be correlated, through the trace elements, to flow through overlying quartz-latite units. In general, this signature persists for only a few tens of meters before it is overprinted by the local rhyolitic signature (Vaniman and Chipera 1996).

**Geochemistry of the Host Rock.** Welded Topopah Spring tuff, the host rock for the proposed repository at Yucca Mountain, is texturally complex yet chemically simple. As described in Section 2.2.1, a critical property for repository development is the presence of a thick, competent and mineable rock mass. The proposed repository horizon is one of the most chemically uniform rock types of the region. However, extensive alteration of the volcanic glass in the rock matrix during and after cooling of the ash flow tuffs has caused variability in rock texture and mineralogy that is not seen in its chemistry. The chemical processes include devitrification (alteration of volcanic glass to a combination of minerals), vapor-phase alteration (rock alteration by volcanic gases during cooling of the ash flow), and the formation of low-temperature alteration minerals after the rock mass had cooled.

The most obvious expression of this variable texture is in the distinctions between zones containing lithophysae (open cavities produced when gas pockets formed as the rhyolite cooled) and those that do not. Based on the textural variations, which include the degree of welding, devitrification and the presence of lithophysae, the volcanic units have been divided into a series of more detailed units. By identifying the texture and mineralogy of alteration in fractures and matrix, studies of these units provide a record of the history of infiltration into the mountain. The detailed mineralogical data have also been compiled in a three-dimensional mineralogical model (Carey et al. 1997) that provides a basis for assessing possible future changes resulting from the thermal and hydrological effects of a repository and potential retardation of radionuclides during transport.

**Fracture and Fault Mineralogy.** As noted above, fracture mineralogy may have a significant effect on both the hydrology and transport properties of the repository system. At Yucca Mountain, the major control on mineralogy is the location with respect to the water table (saturated versus unsaturated). The mineralogy of the unsaturated zone can be further divided by origin, according to whether the minerals were produced at high temperature when the rock was deposited (syngenetic), at lower temperatures after the rock was deposited (diagenetic), or as a result of later groundwater percolation.

Fracture minerals in the unsaturated zone are particularly varied, in contrast to the saturated zone. Unsaturated zone fracture minerals include clay minerals, zeolites, manganese oxide minerals, hematite, calcite, opal, and fluorite. Cristobalite, tridymite, and quartz—all forms of silicon dioxide—occur in unsaturated zone fractures, mostly as syngenetic phases. Cristobalite, however, can occur with opal as diagenetic or percolation-related deposits. The mineralogical variety increases below the proposed repository horizon at the boundary between the devitrified Topopah Spring tuff and the lower vitrophyre of the Topopah Spring tuff where a greater variety of zeolites occur. Calcite and opal are the most characteristic fracture minerals deposited by percolation in the unsaturated zone.

Below the water table, the variety of fracture minerals decreases. Smectite is the only common clay. Manganese oxide minerals occur, and hematite is more common than in the unsaturated zone. The only common silica minerals in saturated zone fractures are quartz and opal-CT. The only common zeolites in saturated zone fractures are clinoptilolite and mordenite, the same zeolites that characterize the altered rock matrix below the water table.

The differences between saturated and unsaturated zone fracture mineralogy may affect transport properties above and below the water table. Based on experiments studying minerals that have the potential to sorb (or accumulate) radionuclides from solution, fractures that contain smectite, manganese oxides, and calcite show particular affinity for plutonium retention.

The available information on fault mineralogy is sparse, but includes smectite, calcite, and clinoptilolite. Information from chlorine-36 studies suggests that, in the unsaturated zone, an understanding of matrix mineralogy may be as important as fault-associated mineralogy in understanding transport. The matrix can interact directly with fluids in areas without fracture mineral coatings.

**Role of Hydrous Alteration Minerals in Yucca Mountain Performance.** The volcanic rocks of Yucca Mountain have been altered to variable degrees since their eruption particularly where portions of the volcanic series cooled quickly and remained glassy. Alteration minerals, such as clays, zeolites, and oxide minerals, can play an important role in restricting radionuclide movement. In addition, syngenetic alteration, involving the interaction of still-hot rock with infiltrating meteoric water, provides a natural analog for hydrothermal alteration that might occur in a repository environment.

A three-dimensional mineralogic model (Carey et al. 1997) has been developed for presenting the mineralogic information in a format accessible for modeling flow, transport, and thermal response. Quantifying mineral abundance and distribution in three dimensions provides a tool for modeling mineral stability and transport. Zeolite, glass, and silica mineral distributions can be modeled in three dimensions to understand long-term thermal response on scales of hundreds of meters. A major conclusion reached from using the three-dimensional model is that zeolitic altered zones are present continuously between the proposed repository and the water table at Yucca Mountain, an important consideration for transport modeling (CRWMS M&O 1998d, Section 6.1). Some previous studies had suggested that zeolites were not present along transport pathways under some areas of the repository.

**History of Large-Scale Alteration at Yucca Mountain.** Detailed examination of the volcanic rocks at Yucca Mountain shows that most zeolite alteration occurred at the same time as tuff emplacement. Early faulting at the site influenced the distribution of alteration. The timing of the major alteration episode was between 13 million and 11.6 million years ago. Although some zeolite formation may have continued later, the major zones of zeolite alteration were defined 11.6 million years ago.

After the formation of major zeolitic horizons, deep-seated fossil hydrothermal activity persisted until about 10 million years ago. Hydrothermal activity 10 million years ago was limited to temperatures of less than approximately 90–100°C (194–212°F), which is the highest temperature at which the zeolite minerals found can remain stable. The fossil hydrothermal system provides an important self-analog for understanding future repository behavior, particularly mineral reaction rates and temperatures (Bish and Aronson 1993). At prolonged exposure to temperatures greater than 90°C (194°F), the sorptive zeolite minerals (clinoptilolite and mordenite) would be altered to a new mineral assemblage (analcime plus quartz and/or calcite).

**Mineral Stability at Yucca Mountain.** In addition to the self-analog studies of past thermally induced alteration events at Yucca Mountain, thermodynamic and kinetic studies provide information on mineral stability from another perspective. This information will be important to understanding how the repository would behave during heating after waste emplacement because mineralogical changes can affect the hydrologic, mechanical, chemical, and transport properties of the rock. Table 2-1 shows four important types of mineral reactions to consider at Yucca Mountain.

Thermodynamic considerations help to explain the observed zeolite mineral alteration. The results of thermodynamic modeling show that the stability of various types of zeolites is a function of silica activity, temperature, sodium concentration in

Table 2-1. Mineral Reactions

| | Reaction | Likely to occur in |
|---|---|---|
| 1 | Volcanic glass ⇒± clinoptilolite ± smectite ± opal-CT | Saturated conditions, at 75°C (167°F) for vitrophyre glass and 45°C (113°F) for vitric nonwelded material |
| 2 | Tridymite/cristo-balite/opal-CT ⇒ quartz | Saturated rocks. The reaction can be greatly accelerated at elevated temperature |
| 3 | Clinop-tilolite/mordenite ⇒ analcime + quartz ± calcite | Saturated rocks that reach temperatures in excess of 90°C (194°F) |
| 4 | Smectite ⇒ illite | Saturated rocks at elevated temperature or in which silica activity is diminished |

water, and the mineralogy of silica polymorphs. Increasing temperature or sodium concentration causes the alteration of zeolites to other phases. However, under present-day conditions, sorptive zeolites show little thermodynamic tendency to react.

Kinetic effects (factors that affect the rates of chemical reactions) are important to consider in assessing the significance of thermodynamic and natural-analog study conclusions. For example, kinetic data suggest that saturated conditions are necessary for any perceptible progress in the four reactions listed in Table 2-1. Therefore, all of these reactions are likely to proceed more slowly in the unsaturated zone at Yucca Mountain than they would below the water table. Similarly, the persistence of opal-CT below the water table indicates that silica reaction kinetics at Yucca Mountain are more sluggish than laboratory studies would suggest. If prolonged temperatures of 100°C (212°F) or more were reached in saturated tuffs, significant progress in all four reactions could occur. However, the thermal design of the repository would limit temperatures above 100°C (212°F) to within the Topopah Spring welded unit, well above zeolitic zones in the Calico Hills unit and the water table.

**Geochemistry, Mineralogy, and Paleohydrology.** Geochemical and petrologic evidence have been used to reconstruct the past hydrology and transport conditions at Yucca Mountain. Vitric to zeolitic transitions imply past water-table rises on the order of 100 m (328 ft), but there is significant uncertainty in the estimate (approximately 20 m, or 66 ft) because of the structural characteristics of the site and uncertainty about the configuration of the transition from unsaturated into saturated rock. Evidence for past trace-element migration in the unsaturated zone may provide insight into the potential for future migration of constituents such as radionuclides. For example, analyses show that strontium concentrations increase at the tops of major zeolitic intervals, which indicates that strontium in percolating groundwater is captured by the zeolitic zones. Similarly, the composition of calcite in fractures indicates a prominent role for minor fracture minerals (manganese oxides) in the transport of heavy metals. Cerium (a lanthanide element) is strongly retained by manganese oxide minerals. This observation shows that even minor fracture minerals can have a significant effect on heavy-metal transport.

**Mineralogy and Sorption Studies.** Many sorption studies have been conducted on samples from Yucca Mountain to investigate the degree to which any released radionuclides would sorb (bind) to minerals encountered along their transport path, therefore slowing their progress towards the accessible environment. Both lithology (rock type) and mineralogy are important in interpreting the sorption experiments. To assess possible transport questions, an understanding of the differences in sorption properties between altered and unaltered rocks (particularly zeolitic versus nonzeolitic samples) is necessary. Also, lithology and mineralogy contribute to the differences in sorption behavior between unaltered rhyolitic and quartz-latitic samples.

Yucca Mountain data indicate that there are three principal mineral groups that may function as barriers to radionuclide migration. The sorptive zeolites (clinoptilolite and mordenite) provide the most continuous and well-defined barriers at Yucca Mountain. Whether their sorptive capacity is strong (as with strontium and cesium) or weak (as with neptunium), their abundance makes them potentially effective obstacles to cationic (positively charged ions) radionuclide transport. Smectites (clay minerals) are not nearly as abundant, but their widespread occurrence virtually ensures that they would be encountered along all transport pathways. Their strong affinity for plutonium makes them a valuable barrier. Manganese oxides are less abundant and not as widely distributed as smectites, but their common association with fractures in the saturated zone—and recent evidence of strong neptunium interactions—suggest that they may contribute significantly to the natural barrier system against radionuclide transport.

### 2.2.5.3 Geochemistry Governing Radionuclide Mobility

**Implications of Geochemical Data for Radionuclide Transport.** Water chemistry influences the sorption behavior of radionuclides and the solubilities of radionuclide compounds. The chemistry of waters that may infiltrate the proposed repository would depend in part on the chemistry of water present in the unsaturated zone above the proposed repository horizon. Therefore, a model for unsaturated zone water compositions must be used as input to near-field corrosion and transport models, and the significance of changes in conditions as a result of repository induced effects (e.g., thermal loading) must be understood. Groundwater compositions beneath the proposed repository horizon would influence the sorption behavior of the radionuclides transported out of the proposed repository horizon.

The expected compositional variation of these waters is limited. The main parameters that could significantly influence transport properties and sorption behavior are pH (a measure of acidity or alkalinity) and Eh (a measure of oxidation potential). The expected range in pH is from 6.5 to 9.0 (very weakly acidic to mildly alkaline). Because sorption properties have been tested throughout this range, the potential effects of pH variation are reasonably well characterized. Some introduced materials (particularly concrete) in the underground environment may affect the pH of solutions, but these effects can be incorporated in the analyses. The expected range in Eh has not been fully defined. Experiments to date, including the single heater test, have largely been carried out under oxidizing conditions, but uncertainty remains concerning the Eh of waters downgradient from Yucca Mountain. Potentially important uncertainties that have not been analyzed experimentally under repository conditions include the significance of concrete-modified water chemistries, the effect of other introduced materials within drifts, or on drift walls, the influence of microbial activity, and the effect of variation in gas compositions on unsaturated zone transport.

Transport properties in the saturated zone may also be influenced by uncertainties related to the heterogeneous distribution of potentially sorbing minerals, as well as changes in geochemical conditions induced by the repository. However, the significance of thermally induced changes in the saturated zone should be less than in the unsaturated zone because of the decreasing magnitude of thermal effects. Saturated zone conditions characterized by reducing, rather than oxidizing, conditions could substantially retard certain radionuclides, thereby enhancing the effectiveness of the natural system.

Geochemical results address the NRC subissue on geochemical and hydrological controls on radionuclide transport and the potential for dilution at Yucca Mountain, which is part of the Key Technical Issue on Radionuclide Transport (NRC 1997a) (see Volume 4, Section 4.3.3.10).

**Radionuclide Solubilities.** One of the initial barriers to radionuclide migration is the solubility (the amount that will dissolve) of the radionuclides themselves in any water that infiltrates the proposed repository. Many of the radionuclides present in spent nuclear fuel have low solubilities under conditions similar to what would prevail in a repository at Yucca Mountain. For those key radionuclides that may be mobile in the repository environment (e.g., neptunium, plutonium, americium, and technetium), solubility depends on the solution chemistry and on the actinide-bearing solid being dissolved.

Long-term solubility experiments for these elements were conducted, along with thermodynamic modeling efforts, to understand the effects of the various species and solid-state precipitates (minerals deposited from solution). This approach involved calculating and measuring the solubility of the least-soluble radionuclide solid phase that might precipitate under conditions anticipated in and near a high-level radioactive waste repository (Nitsche et al. 1994; 1995). This is a conservative approach because, except for uranium, concentrations of radionuclides are likely to be quite low compared to the concentrations of the major elements. Therefore, radionuclides would generally be precipitated in solid solutions of the major elements rather than as pure phases, which are usually more soluble (Gnanapragasam and Lewis 1995; Langmuir 1997). These experimental and modeling efforts have isolated key aspects of radionuclide solubility such as pH, temperature, and Eh.

Because of the heterogeneous and changing conditions, the solubility of radionuclides would vary spatially and temporally across the repository. For performance assessment, it is important to identify the dissolved and solid-state species of the elements involved and the range of solubilities of many radionuclides. Table 2-2 shows the range of solubilities for some key radionuclides expected at the site. These ranges are based on the current understanding of expected geochemical conditions in the repository over time. Because the solubilities of the radionuclides (e.g., neptunium) are quite sensitive to conditions and can vary over several orders of magnitude, uncertainty in environmental conditions can significantly affect performance analyses. Therefore, an improved understanding of the evolution of the chemical environment may decrease the uncertainty in solubilities and other transport properties.

**Sorption and Sorption Modeling.** Once radionuclides have dissolved in water percolating through the site, sorption (binding) of these radionuclides onto the surrounding tuffs becomes a potentially important second barrier. If the radionuclides become attached to materials they encounter along their transport path, their progress toward the accessible environment would be slowed. Sorption includes several physiochemical processes, including ion exchange, adsorption, and chemisorption. Several experimental approaches were used to characterize key sorption-related parameters. Batch-sorption experiments were used to investigate the sorption characteristics of radionuclides. These experiments can be conducted quickly and inexpensively, but they employ static conditions (i.e., the experimental water is not flowing past the material being tested). Dynamic transport studies, in which water flows through the sorbing medium, suggest the results of the batch-sorption studies are generally conservative.

The elements niobium, tin, thorium, and zirconium show strong sorption onto surfaces available in Yucca Mountain rock units. In addition, these elements form solid oxides and hydroxides that have very low solubilities in Yucca Mountain groundwater, especially in near-neutral solutions, like those expected at Yucca Mountain. A high sorption-coefficient value (minimum of 100 mL per gram) is appropriate in performance assessment calculations for all these elements under essentially all conditions expected within the Yucca Mountain flow system.

The elements actinium, americium, and samarium also sorb strongly to surfaces in Yucca Mountain rock units. These elements tend to form carbon-

Table 2-2. Range of Solubilities

| Element | Minimum Value (M) | Maximum Value (M) | Expected Value (M) | Coefficient of Variation | Distribution |
|---|---|---|---|---|---|
| Americium | $10^{-10}$ | $10^{-6}$ | $5 \times 10^{-7}$ | – | Uniform |
| Plutonium | $3 \times 10^{-9}$ | $10^{-6}$ | $5.1 \times 10^{-7}$ | –7 | Uniform |
| Neptunium | $5 \times 10^{-6}$ | $10^{-3}$ | $1.4 \times 10^{-4}$ | 0.20 | Log beta |
| Technetium | Source limited (i.e., not limited by solubility) | | | | |

ates, phosphates, and mixed hydroxycarbonate compounds that are very sparingly soluble. A high sorption-coefficient value (minimum of 100 mL per gram) is appropriate for each of these elements.

The solution and sorption behaviors of plutonium are the most complex of all the applicable elements. The groundwater parameter most critical to plutonium transport in the Yucca Mountain flow system is the redox potential, Eh. The available sorption data suggest that this element should sorb strongly to Yucca Mountain tuffs under most expected conditions. However, uncertainty remains because the redox potential was uncontrolled during these experiments. If sorption coefficients under high redox potential are consistent with earlier results, plutonium could be classified with the strong sorbers and a minimum sorption-coefficient value of 100 mL per gram could be used in performance assessment calculations. If plutonium sorption coefficients are decreased by elevated redox potentials, a different, lower value would be appropriate.

Cesium and radium have high affinities for most Yucca Mountain rock samples, particularly zeolitic samples. A minimum sorption-coefficient value of 100 mL per gram could be used for these elements, assuming cesium concentrations in solution stay low (below $10^{-5}$ M). For strontium, the situation is more complex. Although this element has a high affinity for zeolitic samples, it is not strongly sorbed by devitrified or vitric tuffs. Because the zeolitic tuffs will be a strong barrier for this element, the small sorption-coefficient values obtained to date could be used for devitrified and vitric units.

The sorption coefficient data available for the elements nickel and lead are limited to a dozen or so experiments on nickel. In the surficial environment, lead appears to be less mobile than nickel. Therefore, the nickel sorption coefficients can be used as conservative values for lead. In devitrified and zeolitic zones, a minimum sorption-coefficient value of 100 mL per gram is appropriate for nickel. In vitric zones, sorption coefficients will be in the range from 0 to 50 mL per gram. For vitric zones, an appropriate approach may be to use a random sampling technique to derive nickel and lead sorption coefficients from a normal distribution ranging from 0 to 50 mL per gram.

Yucca Mountain rocks do not strongly sorb the elements neptunium, protactinium, selenium, and uranium. Neptunium appears to sorb primarily by surface-complexation and surface-precipitation mechanisms. The carbonate content of the rocks used in experiments with neptunium appears to have a large impact on sorption behavior. The presence of ferrous iron on tuff surfaces may also be a factor. Protactinium appears to be very insoluble in near-neutral solutions, but its sorption behavior is more complicated. At high pH, protactinium appears to sorb strongly, whereas just below neutral pH, it sorbs poorly. Only lower-range pH experiments have been conducted with Yucca Mountain samples. Selenium will be present as an anion in Yucca Mountain flow systems and will have low sorption affinity. The main unresolved issue is the effect of elevated levels of calcium and magnesium on its sorption behavior. Uranium sorption appears to be controlled by pH, alkalinity, and the concentrations of alkaline-earth ions. Its affinity for Yucca Mountain rock samples is generally low with the highest sorption coefficients observed in zeolitic tuffs. The main gap in the available data are for sorption coefficients on zeolitic and devitrified samples in contact with water enriched in calcium and magnesium at pH values from 6.5 to 8.0.

The elements carbon, chlorine, iodine, and technetium have little or no sorption affinity under the oxidizing conditions expected within the Yucca Mountain flow system. Any retardation of these will involve processes other than sorption. Scientists conducted a batch-sorption study of the effect of naturally occurring organic materials on the sorption of cadmium and neptunium on oxides and tuff surfaces. The model sorbents were synthetic goethite, boehmite, amorphous silicon oxides, and a crushed tuff material from Yucca Mountain. An amino acid, 3-(3,4-dihydroxyphenyl)-DL-alanine, and an aquatic-originated fulvic material, Nordic aquatic fulvic acid, were used as model organic chemicals. These two materials have little effect on neptunium sorption on all sorbents selected for study.

**Dynamic Transport Studies.** Scientists conducted dynamic transport studies to verify the results of batch-sorption experiments. These studies incorporated the component of dynamic flow that the static batch-sorption experiments lacked. Two types of dynamic studies were performed: crushed-rock column and solid-rock column experiments. The solid-rock column experiments used a centrifuge technique (the unsaturated flow apparatus) to simulate flow. These studies suggest that the batch-sorption results are conservative.

**Diffusion Transport.** Diffusion is an important retardation mechanism in fractured media. The unsaturated flow apparatus is an efficient and cost-effective way to study diffusion as a function of saturation in Yucca Mountain tuffs. Diffusion transport studies show that diffusion occurs at varying rates, depending on the size of the diffusing molecule, and that diffusion into devitrified tuff is slower than diffusion into zeolitic tuffs. The diffusion of tritiated water (water with tritium added as a tracer) through saturated devitrified tuffs is about $10^{-6}$ $cm^2$ per second. Large anions, such as some neptunium complexes or pertechnetate, are excluded from the tuff pores because of their size and charge.

Overall results indicate that diffusion from fractures into the matrix occurs even at relatively fast flow rates. Therefore, neptunium may be significantly retarded even if flow takes place largely through fractures rather than through the rock matrix. Retardation of neptunium transport in fractures may be caused by both diffusion into the matrix and sorption onto minerals lining the fracture walls.

**Effects of Colloids.** Colloids are small particles that, when suspended in water, may serve to bind with radionuclides and transport the radionuclides along with the flow. Therefore, they can potentially interfere with processes that would tend to retard radionuclide transport by binding the radionuclides to minerals of the rock matrix or along fractures through which they are flowing. To assess colloid-facilitated radionuclide transport in groundwater at the proposed repository, it is important to understand the generation and stability of colloids, including naturally occurring colloids. Natural colloids may be composed of several minerals, such as clays (e.g., smectites), iron oxides (e.g., hematite, goethite, or other species) or other materials. The tendency of different radionuclides to bind to colloids is a function of the colloid composition. Colloids may also be formed by the alteration of spent nuclear fuel or other man-made materials such as glass or concrete.

The colloid concentration in water samples typical of Yucca Mountain was measured to be on the order of $10^6$ particles per milliliter (for particle sizes larger than 100 nm). At this low particle concentration, the sorption of radionuclides to colloids would have to be extremely high before the colloids could carry a significant amount of radionuclides from the proposed repository to the accessible environment.

Colloid concentration in a given aquifer is a function of the colloid phase stability in the hydrochemical system. Stability is a function of the chemical composition of the water as well as of the hydrogeochemical state of the aquifer. For an aquifer in an equilibrium situation, decreases of the concentration of alkali and alkali-earth elements contribute to an increase in colloid stability and concentration. However, water mixing and large concentrations of organic carbon contribute to an increase in the colloid stability and concentration. Generally, the presence of transient situations such as changes of temperature, flow rate, or chemistry (pH, salt, or redox potential) in the aquifer also induces larger colloid concentrations.

Preliminary results of colloid studies show that hematite and goethite colloids sorbed more soluble plutonium (V) than plutonium (IV) in natural and synthetic groundwaters. Iron oxide sorbed more plutonium in the synthetic groundwater than in the natural groundwater. The percentage of plutonium adsorbed varied with the two iron oxides and the two solutions. Adsorption of plutonium (IV) is a time-*independent* process; adsorption of plutonium (V) is a time-*dependent* process. After a 10-minute contact period, hematite sorbed 57–66 percent of plutonium (IV) colloids and 44–82 percent of soluble plutonium (V); goethite sorbed 29–34 percent of plutonium (IV) colloid and 19–63 percent of plutonium (V). However, the process of plutonium desorption from plutonium-loaded iron-oxide colloidal particles is slow. After 30 days of desorption, plutonium (V) was not desorbed from hematite, and less than 0.01 percent of plutonium (V) desorbed from goethite. Less than 0.01 percent of plutonium (IV) colloids was desorbed from hematite and less than 0.1 percent of plutonium (IV) was desorbed from goethite.

Because there are relatively few data regarding the nature and characteristics of either natural or introduced sources of colloids at Yucca Mountain (or in other similar systems), there is significant uncertainty in current analyses of colloidal transport. Important issues that are being addressed include the relative magnitude of radionuclide migration by colloidal versus dissolved transport (particularly for plutonium) and definition of the effect of variation in the geochemical environment on colloid stability and transport. The reversibility of colloid sorption (the conditions in which colloids may bind or release radionuclides) is also being analyzed. Finally, analysis of examples of possible colloidal transport of radionuclides at the Nevada Test Site, and elsewhere, may provide information relevant to transport models at Yucca Mountain.

The results of all the above studies address the NRC subissue on identifying which radionuclides require some form of retardation to meet performance requirements at Yucca Mountain. This subissue is part of the Key Technical Issue on Radionuclide Transport (NRC 1997a).

#### 2.2.5.4 Modeling of Transport Phenomena

The site-scale unsaturated zone transport model (Robinson et al. 1997) evaluated many different types of conceptual models and numerical methods to simulate the known distribution of environmental isotopes and water chemistry in the unsaturated zone and to assess potential radionuclide transport. Simulated travel times in the unsaturated zone varied widely depending on the selection of parameter sets, but generally showed distinct differences from south to north under the potential repository consistent with the data being collected from the Exploratory Studies Facility. Variability in travel times to the saturated zone ranged from 10 to 10,000 years using three-dimensional simulations. This study found that, if fracture flow is the predominant mechanism and water contacted the waste form, radionuclides could reach the water table quickly if either of the two following conditions existed: if the Calico Hills nonwelded unit is dominated by flow in fractures and radionuclides do not come in contact with zeolites, or if colloid transport is significant for certain radionuclides such as plutonium. An investigation of model sensitivity suggests that current methods underestimate the amount of retardation that will occur, because the models assume that forced fracture flow will bypass most of the zeolites.

Current transport models are subject to significant uncertainty regarding the representation of many of the processes and conditions discussed previously in this section. In addition, several characteristics of the current unsaturated zone model may introduce uncertainties that are unrelated to the process models and parameter distributions used. For example, the model uses a relatively large grid spacing of 100–200 m. This may not adequately represent the local heterogeneity of flux rates, which are highly variable as a result of the spatial variation in infiltration and because of the irregular distribution of fracture pathways. Similarly, the model estimates the dilution in unsaturated zone water by dividing the repository footprint into six subregions, with dimensions about 0.5 by 0.5 km, and distributing the mass of radionuclides released over the total flow in the subregion. Although this representation may be reasonable for periods in the distant future when the repository could be simulated as a broadly distributed source (after many waste packages have corroded), it is probably not reasonable for early releases from the repository, which would likely come from widely spaced point sources (individual failed waste packages). For early releases, knowledge of the magnitude of heterogeneity in the flow system may be important to credible analyses.

An updated, three-dimensional flow and transport model for the site-scale saturated zone was also developed (Zyvoloski et al. 1997). Although model calibration is difficult because of the absence of field data at comparable scales (tens of kilometers and up to thousands of years), the models appear to simulate fracture-dominated flow and flow with pervasive matrix diffusion in a reasonable manner. Further work is in progress to assess transport in systems with flow in both fractures and matrix and with small, but non-negligible, diffusion into the rock matrix.

Currently, in situ flow and transport experiments are being performed at an underground facility at Busted Butte south of the repository locations. The facility has been excavated at the contact between the Topopah Spring tuff and Calico Hills Formation. The presence of both fractured and unfractured rock and various minerals including zeolites will allow scientists to test and evaluate important controls on transport processes below the repository (see Appendix C).

The results of modeling studies address the NRC subissue on evaluating conceptual models and mathematical approaches to modeling radionuclide retardation at Yucca Mountain. This subissue is part of the Key Technical Issue on Radionuclide Transport (NRC 1997a).

#### 2.2.5.5 Status of Radionuclide Transport Studies

Scientists have characterized the solubilities of the radionuclides that might be mobile under the conditions expected to exist at Yucca Mountain. They have also investigated the mechanisms that would tend to slow or reduce the concentration of radionuclides as they move away from a repository. Remaining work will focus on the following: formation of radionuclide-bearing colloids that may bypass retardation mechanisms, retardation mechanisms that might operate in saturated alluvium, and experiments to observe transport and retardation in the field. Results to date of a field transport study at Busted Butte are described in technical detail in Appendix C.

### 2.2.6 Potential Effects of Repository Construction and Operation

Constructing the proposed repository and emplacing high-level radioactive waste would significantly disturb the natural system at Yucca Mountain for thousands of years. Resulting changes caused by excavating the underground drifts and by heat generated by the waste would affect rock mass properties and the nature and rate of processes acting on the repository and its environment. Performance assessments must consider not only natural processes such as groundwater flow, but also the modified processes following construction. Some of the processes most important to performance, such as steam flow and condensation and mineral alteration and precipitation, would not occur without the heat and stress generated by the repository.

The response of the natural system to the combined effects of repository-induced changes is complex and represents a major technical challenge to assessing the long-term performance of the site. Not only are the individual processes complex in their own right, but they are coupled together and interdependent in ways that could significantly affect the future repository behavior. Thus, heat from the waste will substantially change the nature of fluid flow in the mountain. Conversely, flowing water and steam will determine, in part, how the heat is redistributed on a repository scale. Similarly, water flowing in fractures will influence what alteration minerals may form or precipitate. At the same time, the alteration process may change the ability of the fractures to transmit flow and thus change flow paths.

The magnitude of the impacts associated with the repository diminishes with distance. For the reference design in the near-field environment, the rock would undergo large temperature variations, with maximum temperatures in excess of 100°C (212°F). The heat will dry out the rock, lower relative humidity in the emplacement drifts, and cause major changes in rock properties that would only be partly reversed as the rock cools. At intermediate distances up to hundreds of meters from the repository (a region known as the altered zone), temperature variations would be less profound, but permanent changes in hydrologic, geochemical, and other properties would occur. Although the physical processes (e.g., boiling, vapor phase transport, condensation, mineral/rock alteration, variations in geochemical conditions, and mechanical and hydrologic properties) that may affect repository performance are reasonably well understood, there is substantial uncertainty regarding the details of thermal effects, both at a detailed (drift) scale, and at a large (mountain) scale. The uncertainty applies to both the distribution and timing of effects.

Information concerning the effects of a repository on the near-field and altered zone environment addresses the following NRC key technical issues (NRC 1997a):

- Evolution of the Near-Field Environment
- Container Life and Source Term
- Thermal Effects on Flow
- Repository Design and Thermal-Mechanical Effects
- Total System Performance Assessment and Integration
- Radionuclide Transport

These issues are described in more detail in Volume 4, Section 4.3.3.

#### 2.2.6.1 Geomechanical Response to Thermal Loading

The term geomechanics, or rock mechanics, refers to the properties and processes that describe the engineering characteristics and behavior of the rock mass such as the strength of the rock and the stability of mined underground openings. Understanding the geomechanical behavior of the repository is important during the preclosure period when the stability of underground openings must be maintained for operational reasons. Understanding this behavior is also important during the postclosure period when the integrity of the near-field environment may affect the potential for water to contact waste and transport radionuclides.

In response to underground construction and the heat released by emplaced waste (a process referred to as thermal loading), the rock surrounding the proposed repository would experience changes in stress (the forces acting on the rock) and strain (the rocks would be slightly deformed by the induced pressure). During the period of increasing temperature, compressive (squeezing) stress in the near-field rock would generally increase as the rock expands from the heat. Farther away from the source of heat, the expansion could cause tensile (extension) stresses. As the temperature decreases, the overall stress levels would decrease in response to the relaxation and contraction of the cooling rock. Thermally induced stresses may have a significant impact on repository performance because they may alter the characteristics of fractures in the rock, which, in turn, may affect the stability and the hydrologic flow system of the rock formation.

Many mechanical properties of the host rock are known to be temperature-dependent and would change with increasing temperature. Changes may include a decrease in rock strength and development of cracks and fractures in rock near the drift openings. The potential impact on the repository could include changing the mechanical loading on the waste packages as drift lining material and rock fragments fall on them. This would change seepage rates by affecting drift shape and altering the hydrologic properties of the rock matrix.

Strength generally decreases with increasing temperature. Price et al. (1987) report that, for samples from the proposed repository horizon, the mean ultimate strength decreases 16 percent as temperature is raised from 22 to 150°C (72 to 302°F). Work by Martin et al. (1996) indicated that confining pressure has little effect on the coefficient of thermal expansion.

The development of microcracks in the near-field rock over long periods is important because cracking may lead to excavation damage and the formation of rock chips or blocks. The chips or blocks might passively accumulate on the waste package and form transport pathways (i.e., water could migrate through the rock debris to the packages). Drip shields and backfill, if used, could mitigate this process. Martin et al. (1995) performed laboratory experiments to investigate creep (slow movement of the rock mass) in Topopah Spring tuff samples at ambient and elevated temperatures. They found that the observed creep deformation was consistent with a mechanism of crack growth, particularly at high stress levels. Both strength and the stress necessary to produce failure (movement within the rock block) appeared to decrease with increasing temperature.

Modeling of the geomechanical behavior of rock in the near-field environment has been done as part of the repository design and in conjunction with thermal tests (Blair et al. 1997). Nolting and Sun (1997) analyzed drift closure and strength-to-stress ratios up to 150 years after emplacement. Predictions indicate zones of plasticity (where rocks behave as a viscous material rather than as a brittle solid) around the drifts extending approximately 2–3 m (6.5–10 ft) into the wall. Simulations of thermal tests have been done using the two-dimensional version of the geomechanical FLAC code (Itasca Consulting Group, Inc. 1996; Blair et al. 1997). FLAC is an uncoupled thermomechanical model. The stress field depends on the temperature field, but the temperature field is independent of the stress field. Therefore, the thermal field can be solved independently of the mechanical equilibrium problem. The thermomechanical analysis provides a critical link to assessing changes in hydrologic properties by relating permeability modification to slip (movement) on fractures.

Several underground failure mechanisms have been identified that could lead to mechanical loading (accumulation of rocks and lining materials) on the waste package (CRWMS M&O 1998d, Section 7.4.3.3). They include the following:

- Block failures. Blocks could fall into open spaces left by a collapsed ground support system. Block failures are the most credible loading scenario.

- Rock burst failures. Such failures are unlikely, even if ground support fails.

- Rock creep. Openings close, forcing ground support segments onto the package or backfill.

- Sloughing of rock materials into openings created by failed ground support systems.

As time passes in a closed repository, the various failure mechanisms could result in the waste packages being covered with debris. This debris would form a thermal, insulating blanket around the waste package and could cause any water that seeps into the open drifts to be diverted either toward or away from the waste package.

The amount of pressure load experienced by individual waste packages would depend on the design of the near-field environment and particularly on whether backfill of the drifts is included. Rock mass conditions would likely be quite variable across the repository, which would also affect the integrity of the drift openings. If backfill is present, creep closure of the drift openings could transmit pressure through the backfill. If sufficient long-term creep occurs and the openings around the waste packages are closed, then a full lithostatic load (pressure equal to the weight of the overlying rocks) might be imposed. Without backfill, uniform loading of the waste packages could result only in the unlikely event that complete and uniform creep closure of the openings occurred after the uniform and complete failure and crumbling of the support system.

No direct data are available to address creep over long time frames (10,000 years), but there is no indication that full lithostatic loading is likely to be imposed. Natural openings in other rock types are known to have remained open over long periods (e.g., limestone caves and lava tubes), but no specific study of the behavior of tuffs has been completed.

Once a repository is closed, the ground support system will degrade and eventually collapse. It may collapse (fail) in such a way that it remains generally intact but falls down and rests on the waste packages. In this case, any rocks that fall into the opening after the ground support system has failed will land on the failed liner; the mechanical load of the rock will be transferred through the liner to the waste package.

Alternatively, the ground support system may collapse in such a way that pieces of the lining fall to the side of the waste packages. In this case, the rocks that fall from the opening could pile up directly on the waste package.

The size and weight of blocks that could move into the space left by a collapsed lining depend on fracture spacing and, ultimately, on the opening dimensions that result from the ground support failure. The ultimate bound on this opening dimension would be the full drift diameter, but the actual dimension should be somewhat smaller because total failure of the ground support is unlikely.

Information on the geomechanical response to thermal loading addresses the NRC subissue on consideration of thermal-mechanical effects on underground facility design and performance. This subissue is part of the Key Technical Issue on Repository Design and Thermal-Mechanical Effects (NRC 1997a) (see Volume 4, Section 4.3.3.6).

#### 2.2.6.2 Geohydrological Response to Thermal Loading

The heat associated with waste emplacement would affect the repository by changing both the hydrologic properties of the rock and the nature and rate of flow processes. These changes would affect repository processes at all scales, ranging from flow in individual fractures to the transport processes at a mountain scale. Information on these processes addresses the NRC subissue on the effects of coupled processes on the rate of seepage into the repository, which is part of the Key Technical Issue on Evolution of the Near-Field Environment (NRC 1997a) (see Volume 4, Section 4.3.3.3). It also addresses the subissue on whether the DOE thermal-hydrologic testing program, including performance confirmation testing, is sufficient to assess the potential for thermal reflux to occur in the near field. This subissue is part of the Key Technical Issue on Thermal Effects on Flow (NRC 1997a).

As described in Section 2.2.1, the welded Topopah Spring tuff, which includes the proposed repository horizon, is fractured, and fluid flow occurs primarily through the fractures. In the near field, temperature-induced changes in the stress field may affect fracture properties. Increased compressive stress would generally cause a reduction of the fracture aperture (width of fracture opening) and a corresponding decrease in fracture permeability (the ability of the fracture to transmit fluid flow).

Increasing the level of stress in the rock, however, may also cause certain fractures that are favorably oriented to displace or move. Olsson and Brown (1994) and others have shown that this movement, called shear displacement, may increase the fracture aperture and so may increase the permeability. Field measurements from tests at G-Tunnel at the Nevada Test Site (Lee and Ueng 1991) indicate that rock mass permeability increased during heating and did not return to initial levels upon cool-down. This indicates that a mechanism other than closure of fractures dominates fracture flow behavior. Even though some fractures may close during heating, others could open, creating new paths for flow. More recently, Barton et al. (1997) presented convincing evidence that potentially active normal faults in the Dixie Valley geothermal field are hydraulically conductive. These faults are critically stressed, which means that the stress is almost equal to rock strength, and the faults are close to movement. This observation is significant because it may provide a means to identify hydrologically conductive features.

Although some faults clearly have enhanced permeability and are pathways for water flow, others (e.g., some normal faults) have lower permeabilities than surrounding rocks and act as a barrier or dam to groundwater flow. It is unclear whether fault movement, mineral alteration, or fracture filling causes this variation in hydrologic properties. Nevertheless, many laboratory studies and field observations (Bandis et al. 1983; Barton et al. 1985; and Wilder 1987) have documented that lateral movement on faults or fractures (shear displacement) appears to enhance hydrologic flow properties more than movement down the dip of the fracture plane (known as normal deformation).

In addition to the effect on rock properties, the high initial heat flux caused by radioactive decay would influence the nature and rate of fluid flow within the mountain. Although the rate of heat production would decrease rapidly with time after emplacement, thermal processes would dominate the distribution and movement of air, water vapor, and liquid water in the unsaturated zone for hundreds to thousands of years following repository closure. Decay heat may cause boiling conditions to persist in the near field for hundreds of years at the edges of the potential repository, and for up to thousands of years at the center of the repository (CRWMS M&O 1998a, Section 3.7.7). In most repository behavior analyses using realistic assumptions about waste characteristics and repository loading strategies, it appears that the vertical extent of the boiling zone extends to approximately the top of the Topopah Spring tuff, roughly 100 m (328 ft) above the repository horizon, at the center of the repository. The extent of boiling decreases to several tens of meters near the edges of the repository.

System response to the induced heat load determines the characteristics of the near-field environment, including the temperature, relative humidity, gas-phase and air-mass fraction, and the quantity and quality of liquid water present at different locations within the engineered barrier system. The heat load would also produce mechanical changes and mineralogical changes in a large volume of rock surrounding the repository. The zone of significant modification is known as the altered zone, and it may extend vertically throughout most of the unsaturated zone and to some distance below the water table.

As shown conceptually on Figure 2-21, the thermally driven transport of water and water vapor away from the heat sources in the repository would cause a redistribution of the pore fluids, including:

- Dry-out zones, in which the liquid-phase saturation and relative humidity are less than ambient (pre-emplacement) conditions
- Condensation zones, in which the liquid-phase saturation is greater than ambient
- A region in which the gas-phase is dominated by water vapor, which has displaced air

These effects, which would vary as a function of time (see Figure 2-21), would influence both the amount of liquid water in contact with waste after emplacement and the chemistry of the water. Both parameters play a major role in determining the potential flux of radionuclides from the near-field environment. The air and water content of the gas phase (the air-mass fraction) is important to the geochemistry of the repository environment, because it determines the amount of oxygen available, which affects waste package corrosion rates.

Waste-generated heat flows away from the drifts by conductive and convective heat-flow processes. Conduction involves heat transfer mainly through the rock mass, whereas convective heat flow occurs mainly through the movement of liquids and vapor through the rock. Two convective processes (heat pipes and buoyant gas-phase convection) could significantly influence the temperature distribution in the near field and altered zone. Heat pipes result when vapor flows away from the heat source and liquid condensate flows toward the heat source simultaneously. The location of the heat-pipe effect is strongly influenced by the amount of natural percolation flux (CRWMS M&O 1998a, Section 3.2.2). Higher percolation flux suppresses rock dry out and increases the tendency for heat pipes to form near the hot emplacement drifts. Lower flow rates favor rock dry out and decrease the tendency for heat-pipe development near drifts. Buoyant gas-phase convection results when heated air flows upward and outward from heat sources. This mechanism requires large rock-mass bulk permeability and fracture networks that are ubiquitously connected over large vertical distances. The work described in Section 2.2.3 indicates that such networks are well developed in the Topopah Spring welded tuff.

Heat flow in the rock causes a temperature buildup in the near field and altered zone as well as in the proposed repository engineered barrier system. The temperature buildup depends strongly on the thermal-loading conditions imposed by the emplacement of waste packages. The overall

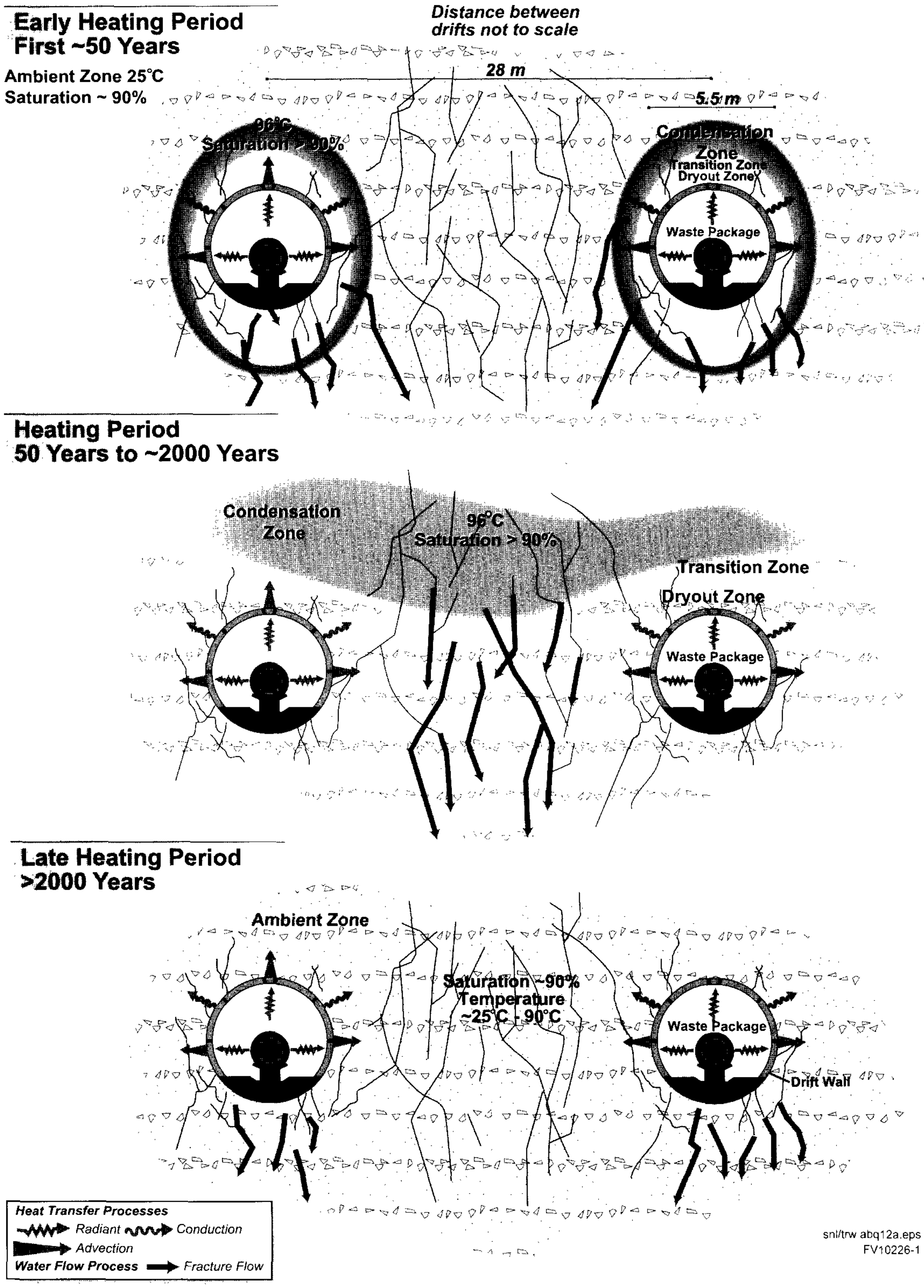


Figure 2-21. Conceptual Thermohydrologic Processes Important to Repository Performance for Three Time Periods

repository thermal-loading conditions are analyzed using the areal mass loading, which integrates the combined effects of many packages at a repository scale. However, variations in heat output and rock properties near individual waste packages strongly influence local thermal-hydrological conditions in the emplacement drifts and on the waste package surfaces. Therefore, repository performance analyses also must consider variability in the detailed processes (such as seepage and dripping onto waste packages) that would occur.

Gas-phase, convective heat-transfer (the flow of heated gas) increases the overall efficiency of heat transfer away from emplacement drifts, and therefore decreases near-field temperature buildup. If heat pipes extend from the boiling front all the way back to the repository horizon, near-field temperatures cannot increase much above the nominal boiling point (96°C, or 205°F). If buoyant gas-phase convection (e.g., at a mountain-scale) is significant, near-field temperatures would be decreased, particularly at the edges of the repository. A key issue to be addressed by large-scale thermal testing and analysis is the extent and relative influence over time of both conduction and convection on a repository scale. In particular, the relative contribution of heat pipes and buoyant gas-phase convection to the total heat flow around emplacement drifts and in the repository is important to postclosure performance because these processes directly affect fluid flow.

As the steam generated by boiling in the near-field environment moves outward, it would eventually condense back to liquid water and begin flowing downward. The vertical extent of heat induced, liquid-phase flow includes the heat-pipe zone above the repository horizon and the condensate-drainage zone below the repository. Both of these zones are regions where the total liquid-phase flux is greater than the ambient percolation flux. The amount of liquid-phase flow in these zones would be greatest immediately after waste package emplacement and initial heating and boiling, and this flow would decay continuously until it reached the value of the background percolation flux. Model simulations suggest that the condensate drainage zone may reach the water table within 100 years (CRWMS M&O 1998a). Although the liquid-phase flux (the total volume of flow) in the heat-pipe zone would continuously decline, the length of the heat-pipe zone would continue to expand during the first 500-years on average. The length of the heat-pipe zone, as well as the time required to attain its maximum length, would increase with repository depth.

Rock dry out is the result of the balance between the rate of vaporization and vapor transport away from emplacement drifts and the rate of return of liquid-phase flow to the dry-out zone. Two mechanisms influence the rate of rewetting:

- Gravity-driven percolation and condensate flux in fractures

- Capillary-driven matrix imbibition and wicking in fractures

Superheated conditions, resulting in rock dry out and a reduction in relative humidity in the repository rock, would occur if the amount of heat is sufficient to evaporate all of the local incoming water. If the volume of incoming water is too large, the heat generated by waste would be insufficient to generate superheated conditions. If the amounts of evaporation due to heat, condensation, and percolation of water are balanced, heat-pipe conditions, characterized by evaporation and upward transport of water vapor, and contemporaneous condensation and downward transport of liquid water would occur.

The local heat flux in the repository would be proportional to the amount, age, and distribution of waste. Local spatial variability in either the heat flux or the liquid-phase mass flux may result in regions where the local liquid-phase flux would prevail (Wilder 1997, p. 34). Because the heat flux is greatest at the waste package, and it decreases away from the drifts, local liquid-phase flow is more likely in between drifts (e.g., at the pillar centerline, as shown on the middle sketch of Figure 2-21) rather than near the drift. Conversely, vapor phase flow and drying are more likely where heat flux is high near the drift. This mechanism may allow the repository to shed significant volumes of water that have bypassed repository drifts and have not been in contact with waste.

Thermal-hydrological conditions in the engineered barrier system are affected by both natural systems and processes and by the design of the near-field environment (including potential design features such as backfill or drip shields). The key factors that affect thermal and hydrologic conditions include the following:·

- The effect of mountain-scale heat flow on lateral heat loss from the repository
- Repository-scale variability in ambient percolation flux
- Waste package-to-waste package variability in heat output
- Matrix-imbibition diffusivity of the local host-rock unit, which influences the rate of rewetting of the dry-out zone by capillary-driven matrix imbibition
- Wet and dry thermal conductivity of the local host-rock unit (temperature buildup in the near field and engineered barrier system would increase with decreasing thermal conductivity)
- Depth of the repository below ground surface (also called overburden thickness, the duration of the boiling period increases with repository depth)

All these factors are considered in the multiscale, thermal-hydrological modeling approach used by the TSPA (Volume 3). Limited subsystem modeling suggests that the variation in hydrologic properties due to thermal effects is less than the natural variability already incorporated in performance analyses. However, there is significant uncertainty regarding this conclusion. At both the local (drift) scale and at a mountain scale, there is little information available to test or calibrate model predictions of the distribution, extent, or timing of hydrologic effects such as rock dry out or rewetting. Current models do not explicitly incorporate the effects of mineral precipitation (in fractures, or as a cap above the repository horizon), on hydraulic properties or flow paths, or the impact of chemical changes on the potential transport of radionuclides. Similarly, the potential impacts of variation in flow properties in the near field due to loss of mechanical stability (collapse) of the drifts, or changes in fracture-matrix interaction, are not directly incorporated in performance models.

Heat-driven changes to the liquid-phase saturation and liquid-phase flux distributions in the unsaturated zone are long-term transient changes associated with the effects of evaporation and condensation. In principle, the mountain would eventually return to something resembling its initial state, except for the effects of climate change, after decay of the thermal pulse and rewetting of the dry-out zones. However, the thermal-hydrological disturbance would also generate thermochemical and thermomechanical alteration of hydrologic and transport properties, particularly in the fractures, in both the unsaturated and saturated zones. Some changes, such as fracture closure that would result from thermal-mechanical effects, may be temporary. Others, such as the filling of fractures that results from thermal-chemical effects, may be permanent.

### 2.2.6.3 Geochemical Response to Thermal Loading

The geochemical conditions and processes that would prevail after waste emplacement would be affected by the heat generated by the waste and by the hydrological regime associated with that heat. Elevated temperatures would cause several coupled processes that link the system mineralogy, geochemical environment, and hydrology. These processes include dehydration, rock and water interactions and chemical reactions, and changes in the rock mass and chemistry of water. The consequences of geochemical effects would depend on the rate of temperature change, the maximum temperature reached, and the flux of water and vapor through the rock. In general, geochemical interactions would be affected in several ways. First, increased temperature usually causes an increase in the rate at which reactions proceed. Second, most chemical reactions are also temperature-dependent. Mineral solubilities, aqueous speciation, and equilibrium-phase assemblages all depend on temperature. As temperatures change, the directions of reactions may also change, and new phases may replace minerals that were previously stable. Information on these processes addresses the NRC subissue on the effects of coupled processes on the rate of seepage into the repository, which is part of the Key Technical Issue on Evolution of the Near-Field Environment (NRC 1997a) (see Volume 4, Section 4.3.3.3).

The addition of man-made materials in the near-field environment would also modify the chemical environment and influence reactions that may occur (Figure 2-22). Two volumetrically and chemically significant added materials are cementitious materials (concrete, grout, and their alteration products) used in repository construction and corrosion products derived from the waste packages. Cementitious materials are alkaline, and would affect the chemistry of water flowing through the system, increasing pH (higher alkalinity). Metal oxidation can affect the oxidation state, or redox potential of the environment, and may be the source of colloidal material for radionuclide transport.

Geochemical interactions near a repository would vary both spatially and over time. The evolution of environmental conditions has been divided into three generally distinct time periods. During the initial heating period, liquid water would be present until temperatures rise sufficiently and boiling commences. This initial phase ends when all liquid water in the near field has boiled off. The second period is characterized by a steam-domi-

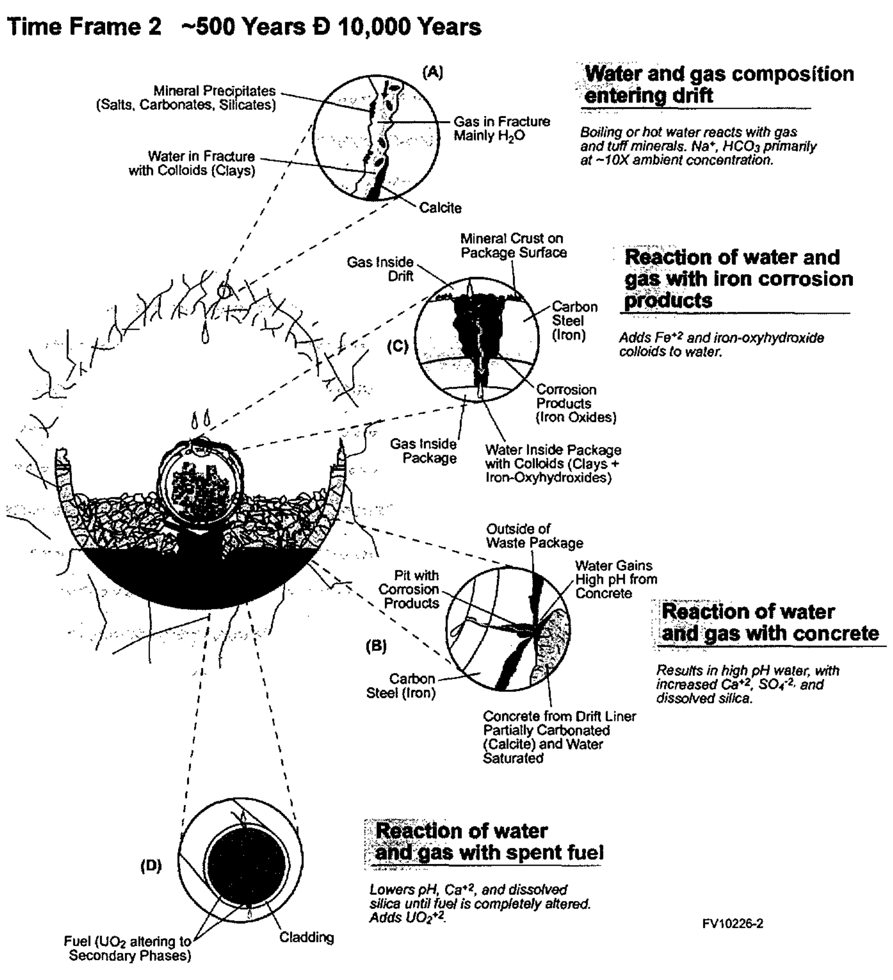


Figure 2-22. Conceptual Geochemical Processes at Repository Drift Scale that May Affect Performance

nated vapor phase in the pore and fracture volumes and a total, or very near, absence of liquid water near the repository. Temperatures in the dry- out zone may rise to well above the boiling point and eventually decline. The final geochemical regime begins when the temperatures have fallen sufficiently that liquid water can reappear by inflow or condensation. Geochemical interactions and reactions will be most widespread and fastest in the first and third periods, when liquid water is present (with or without steam). Even at maximum likely near-field environment temperatures, the rates of most reactions involving a vapor phase in the absence of liquid are generally negligible as are the rates of most solid state transformations.

One of the most prominent likely effects is the redistribution of silica in the unsaturated zone (e.g., dissolution of cristobalite followed by precipitation of chalcedony, opal, or quartz). Because most of the dissolution and reprecipitation would occur in fractures where water is flowing, this reaction may be sufficient to open new pathways for fluid circulation and close off or reduce old ones. Redistribution of minerals (solution or precipitation) along fracture walls and in adjacent matrix could also affect the ability of water to be imbibed into the rock matrix (Matyskiela 1997). The formation of phases such as smectite (a clay mineral) and manganese oxides, though quantitatively minor, may nonetheless have a significant effect on subsequent radionuclide retardation. This would be due to high sorption capacities (including ion exchange) and the concentration of these phases along preferred flow paths (mainly fractures). Calcite, the major mineral in the fractures of the proposed repository zone, would be expected to dissolve in condensate zones and increase fracture porosity in those areas.

Understanding the chemical processes that would occur in a repository environment requires integrating concepts and data obtained from field studies of natural analogs and laboratory studies of similar processes under accelerated conditions. Several relevant studies are summarized here.

**Hydrothermal Alteration of Devitrified and Vitric Tuffs.** Knowledge of the alteration mineralogy of the tuffs as a function of temperature is important because of the effect of mineralogy on transport properties. Devitrified tuff from the repository horizon and vitric tuffs from the underlying Topopah Spring welded unit were reacted with Yucca Mountain groundwater in well-mixed systems at temperatures ranging from 90°C to 350°C (194°F to 662°F) for up to 303 days (e.g., Knauss et al. 1985; Knauss 1987). Detailed analyses were made of the evolving fluid chemistry and of the mineralogy and chemistry of the reacted tuffs. Zeolites were identified as alteration products in most of the runs at 150°C and 250°C (302°F and 482°F) (mordenite and dachiardite were identified in runs with devitrified tuff, and clinoptilolite was identified in runs with vitric tuff). No zeolites were observed forming in experiments below the boiling point of water at 90°C (194°F). Reaction of naturally zeolitized tuff at 90°C and 150°C (194°F and 302°F) resulted in a change in the composition of the zeolite, heulandite (which became more potassium-rich), but there was no evidence of dissolution. Around 90°C (194°F) and below, zeolites appear to be slow to form on laboratory time scales. The most prominent change in the water chemistry was the increase in the concentration of aqueous silica. In systems with devitrified tuff, this concentration appears to be controlled by cristobalite solubility. In systems with vitric tuff, the aqueous silica concentrations are higher, approaching the solubility of amorphous silica. The EQ3/6 computer code (Wolery et al. 1990) was successfully used to model many of these runs, accounting for thermodynamics, kinetics, and metastability on laboratory time scales (Delany 1985).

**Changes in Sorptive Properties of Zeolites.** Determining changes in the sorptive properties of zeolites requires analyzing ion-exchange behavior at elevated temperatures. Clinoptilolite is the most abundant cation exchanger at Yucca Mountain, and its properties would affect the transport of radionuclides. Models have been developed to analyze the stability and composition of clinoptilolite and its cation exchange properties as environmental conditions change during heating and cooling (with both liquid water and vapor).

Tests of the ion exchange model show that adsorption of trace quantities of radionuclides, such as cesium and strontium at 25°C (77°F), can be adequately modeled. There is good agreement between model prediction and measurement for strontium sorption over a wide range in sorption coefficient values. For cesium, the model underestimates sorption for most of the smectite-rich samples and for samples with low cation exchange capacities. However, further work by Viani and Bruton (1996) has successfully simulated cesium sorption on the clays.

Simulations show that sorption is very sensitive to clinoptilolite composition. For this reason, changes in clinoptilolite composition that might be caused by interactions with proposed repository components must be considered when analyzing sorption. For example, fluids that have interacted with calcium-rich cement could migrate into surrounding host rock and cause clinoptilolites to become more calcium-rich. This would decrease their sorptive capacity.

The generally good agreement between model predictions and sorption measurements means that the significant mineralogical database for Yucca Mountain (Bish and Chipera 1986; Broxton et al. 1986) can be used to predict cesium and strontium sorption distribution coefficients for tuffs lacking sorption data. The effects of temperature and solution composition on sorption, which are required to model the long-term sorptive behavior of clinoptilolite, can also be assessed using the ion-exchange model. Calculations suggest that increasing temperature decreases the tendency for cesium to sorb onto clinoptilolite but favors sorption of strontium.

**Using Natural Analogs to Gain Confidence in Geochemical Modeling.** The capabilities and limitations of geochemical modeling codes such as EQ3/6 (Wolery et al. 1990; Wolery and Daveler 1992) and thermodynamic databases have been tested by analyzing natural hydrothermal systems that have some mineralogical and environmental similarities to Yucca Mountain. Specifically, EQ3/6 was used to simulate mineral-fluid relations in the Wairakei geothermal field in New Zealand (Bruton 1995). Comparisons between observed mineral assemblages and model simulations of equilibria were used to evaluate the thermodynamic database for various environmental conditions.

The results of modeling are generally consistent with observed vein and matrix mineral equilibria at Wairakei for fluids at temperatures greater than 240°C (464°F). Some geochemical databases simulated observed relations better than others; therefore, these data were incorporated in the model for future simulations.

Both field data and model results indicate that stable mineral assemblages can be significantly impacted by small differences in fluid chemistry, temperature, or pressure. Because of this sensitivity, and the degree of heterogeneity in both mineralogy and environmental conditions, geochemical models cannot precisely predict the spatial or temporal evolution of alteration in detail. However, the results of analog studies, and simulations of Yucca Mountain behavior, suggest that modeling with EQ3/6 and similar tools (combined with knowledge of geology) can provide important insight into the mineralogical and fluid chemistry evolution of the repository system. The model results also provide an important input to performance analyses.

**Reactive Transport Simulations of Tuff-Water Interactions.** The dissolution and precipitation of minerals during repository heating and cooling may significantly affect the hydrologic properties of the site by increasing fracture porosity and permeability in some areas and decreasing it in others. Porosity modification was monitored during dissolution and precipitation of a wide range of silicates along a flow path similar to that expected for water condensed from steam generated in the near-field environment (Wilder 1997, Section 5.4.5). The results show that porosity may more than double in devitrified and welded tuff due to the dissolution of cristobalite in the regions immediately adjacent to the condensation front. As these waters migrate laterally and downward, the dissolved constituents eventually precipitate out as complex silicates (zeolites, clays and hydrated aluminosilicates) forming altered regions with reduced porosity. The complex coupling of fluid flow and reactive chemical transport demonstrates that large changes in bulk rock hydrologic properties may occur within a few hundred years of repository operation. The condensation zone may remain in place for thousands of years. Therefore, the alteration processes affecting hydrologic properties may be sustained.

**Expected Groundwater Chemistry and Secondary Mineralization.** The effect of temperature and uncertainty in reaction progress due to kinetics on fluid composition was analyzed for devitrified and vitric tuffs interacting with J-13 well water over a range of temperatures (CRWMS M&O 1998a; Knauss et al. 1985; Knauss and Peifer 1986; Knauss et al. 1987; Knauss 1987). For these simulations, fluid was in equilibrium with atmospheric gases. The results indicate that water compositions remain mildly oxidizing and slightly to mildly alkaline (pH between 7.5 and 8.8) for most conditions. However, when very large volumes of vitric material interacted with relatively small volumes of water, the buffering effect of atmospheric gases was overwhelmed and the solution became acidic. This may be the case for only small volumes of water, but this result has not been fully evaluated. It appears to be a result of the oxidation of one or more trace components in the vitric material and may, therefore, depend strongly on the exact glass composition used in the model. Secondary minerals that formed in these simulations were sensitive to the extent of reaction and temperature. In most cases, zeolites and clays were formed with minor amounts of other minerals. The uncertainty in the time at which secondary minerals actually form can be as great as hundreds to thousands of years.

**Mineral and Water Chemistry Changes During Evaporation.** The evaporation of ambient groundwater, represented by J-13 well water, was simulated by EQ3/6 calculations for 95 to 98 percent water removal (CRWMS M&O 1998a; CRWMS M&O 1998d, Section 7.5.3.8). Calculations were made under two conditions. In one, solvent water was merely removed from the system. In a more realistic case, oxygen gas and carbon dioxide partial pressures were fixed at atmospheric values as solvent water was removed. Comparison of the results showed that the loss of carbon dioxide from the groundwater to a co-existing gas phase causes a dramatic increase in pH. Up to 98 percent water removal, the solution becomes more concentrated and calcite is the principal mineral precipitate. Small amounts of dolomite, smectite clay, and possibly the zeolite stilbite also form. At higher degrees of water removal (representing total dry out), halite, soda niter, and gypsum would be expected to form, along with other highly soluble salt minerals.

Mineralogical and fluid chemical modeling results are expected to be the foundation upon which refined analyses of unsaturated zone flow and transport are developed. These analyses will assess the effect of mineralogical changes on important flow properties and processes. These analyses will also assess a range of potential repository scenarios including differing waste emplacement strategies. To successfully evaluate repository performance, it will be necessary to demonstrate an understanding of the effects of site geochemical evolution.

#### 2.2.6.4 Status of Near-Field and Altered-Zone Studies

Scientists have carried out field tests to examine how waste-generated heat would affect processes taking place in a repository. Results from these studies and from laboratory studies provide input to models of near-field and altered-zone processes. These results address the NRC subissues on effects of coupled processes on radionuclide transport through engineered and natural barriers and on effects of coupled processes on the rate of seepage into the repository, which are both part of the Key Technical Issue on Evolution of the Near-Field Environment (NRC 1997a) (see Volume 4, Section 4.3.3.3). Future work will focus on completing the ongoing field thermal tests, carrying out a new thermal test in the cross-drift, and updating models. Studies will also support design of a potential repository by modeling the effects of design options and alternatives and by testing materials that may be used in a repository.

### 2.2.7 Potentially Disruptive Events

Performance analyses of a potential repository at Yucca Mountain consider the present-day environment and how presently active processes, such as groundwater flow, may change over time. These performance analyses also consider potential effects of unexpected or low probability events. Demonstrating acceptable performance in light of these events forms one element of the postclosure safety case (see Section 1.8.1.3). For Yucca Mountain, three categories of natural environment events possibly could lead to radionuclide release:

- Volcanic hazards or the potential for a volcanic eruption to disrupt a repository
- Seismic hazards or the potential for earthquake ground shaking or fault displacement to lead to releases
- Human intrusion caused by the inadvertent penetration of the repository during potential exploration for valuable resources

The following discussion addresses the likelihood of these events and their potential consequences. These scenarios have been explicitly considered and incorporated in repository performance assessments. The assessments described in Volume 3 also consider the consequences associated with each type of disruptive event. Current analyses indicate that the impact of each scenario on performance is low.

One additional disruptive event has been identified that could affect repository performance: the possibility that radionuclide migration could cause nuclear criticality and the production of fission products. Criticality is not discussed in this volume because it is not a natural system process. The possibility of criticality is discussed in Volume 2, which describes the design of the potential repository.

#### 2.2.7.1 Igneous Activity and Volcanic Hazard

During the initial characterization of Yucca Mountain nearly 20 years ago, the existence of young basaltic volcanism in the region was identified as a potential hazard to a repository. The Lathrop Wells cinder cone is estimated to be approximately 75,000 years old, which suggests that possible volcanic disruption needs to be evaluated. Therefore, DOE performed extensive investigations to determine the ages and nature of past volcanic episodes and to better understand the tectonic setting. Scientists performed subsequent volcanic hazard analyses based on this extensive data. Results of these investigations address the NRC Key Technical Issues on Igneous Activity, Total System Performance Assessment and Integration, and Activities Related to Development of the U.S. Environmental Protection Agency Yucca Mountain Standard (see Volume 4, Section 4.3.3).

Regional volcanism can be divided into two stages: silicic and basaltic. Silicic volcanism, which is characterized by the eruption of large volume ash flows, created the southwestern Nevada volcanic field and Yucca Mountain between an estimated 15 million to 7.5 million years ago. These caldera-forming eruptions occurred during a period of intense tectonic activity. This activity was associated with active geologic faulting caused by rapid extension of the earth's crust. The most voluminous silicic volcanic activity in the Yucca Mountain region occurred between 15 million and 11 million years ago (Sawyer et al. 1994). Based on geology of similar systems in the Great Basin, it appears that the silicic volcanic cycle is complete and will not recur.

Basaltic volcanism near Yucca Mountain began approximately 11 million years ago and has continued into the Quaternary period. One episode of basaltic volcanism occurred between 9 million and 7.2 million years ago; a second occurred between 4.7 million and 0.075 million years ago. The basaltic volcanic events were much smaller in magnitude and less explosive than the silicic eruptions. They generally were typified by the formation of the small volcanoes or cinder cones in Crater Flat and Lathrop Wells. The eruption volume of individual basaltic volcanic events has also been decreasing progressively through time. The decreased rate of volcanic activity correlates with the decreased rate of regional extension and faulting.

To assess the likelihood of volcanic activity disrupting a repository, DOE has performed numerous analyses and conducted extensive volcanic hazard assessments (Crowe et al. 1993). A panel of 10 experts representing a wide range of expertise in the fields of physical volcanology, volcanic hazards, geophysics, and geochemistry conducted the most recent assessment (CRWMS M&O 1996b). The scientists reviewed extensive information presented by representatives of DOE, USGS, the State of Nevada, NRC, and others regarding the spatial and temporal distribution of future volcanic activity near Yucca Mountain. This information included a careful evaluation of the uncertainty in all the analyses. These experts assessed the likelihood that future volcanic activity could occur at or near the repository.

The panel estimated that approximately $1.5 \times 10^{-8}$ volcanic events per year could disrupt a potential repository. This translates to approximately one chance in 7,000 of a volcanic event disrupting the repository during the first 10,000 years after closure, or one event per 70 million years. The findings are comparable to the estimates previously published by DOE (Crowe et al. 1993). These results address the NRC subissue on the probability of igneous activity, which is part of the Key Technical Issue on Igneous Activity (NRC 1997a) (see Volume 4, Section 4.3.3.1).

The findings of the expert panel closed the study of volcanic hazards at Yucca Mountain because the remaining volcanic hazard assessment uncertainties are unlikely to be reduced by further investigations.

### 2.2.7.2 Earthquakes and Seismic Hazard

Seismic risk to a potential nuclear waste repository is greatest during the repository operational phase when buildings and equipment for handling nuclear waste will be operational. However, seismic activity may also present a risk following facility closure if earthquakes or faulting affect underground openings or the integrity of waste packages. Assessing seismic hazards at Yucca Mountain has focused on characterizing ground motion and fault displacement associated with future earthquake activity near the site. Results of these investigations address the NRC Key Technical Issues on Structural Deformation and Seismicity, Repository Design and Thermal-Mechanical Effects, and Activities Related to Development of the U.S. Environmental Protection Agency Yucca Mountain Standard (see Volume 4, Section 4.3.3).

Modern seismicity has been monitored at the Nevada Test Site since 1968. In 1979, a network of seismic stations was established in the Southern Great Basin to monitor earthquakes near Yucca Mountain (Rogers et al. 1987). The largest earthquake detected by the monitoring network was the magnitude 5.6 event near Little Skull Mountain on June 29, 1992. Aftershocks from this earthquake have provided a wealth of new data to study ground motions.

In addition to contemporary monitoring and seismicity analysis, site characterization activities also have focused on understanding the last 1 to 2 million-year history of active faults in the Yucca Mountain vicinity (Whitney 1996). Faults within 100 km (62 miles) of Yucca Mountain were examined using aerial photographs. All faults with suspected Quaternary movement were evaluated. Natural exposures were cleaned, and about 50 trenches were excavated across faults within and near the site. Eleven more trenches were excavated on the Bare Mountain and Rock Valley faults. Although these two faults are farther removed from the site, their lengths suggest they could produce large magnitude earthquakes that could create strong ground motion at the site.

Information from these trench studies indicates that estimated slip rates for faults at Yucca Mountain are low, varying from 0.0001 mm per year (0.000004 in. per year) to 0.04 mm per year (0.002 in. per year) (Whitney 1996, Chapter 4). Offsets of the earth's surface range from 3 to 170 cm (1.2 to 67 in.) per large event (Whitney 1996, Chapter 5). The average time interval between surface displacement events varies from 13,000 to 100,000 years or more (Whitney 1996, Chapter 4).

Ground motion studies for Yucca Mountain have been conducted to investigate the level of shaking produced by local and regional earthquakes and the rate at which the shaking attenuates with distance. Studies have included investigating local site amplification effects (Su et al. 1996), developing a relation representing regional ground motion attenuation (Spudich et al. 1997), and modeling ground motion from hypothetical earthquakes (Schneider et al. 1996).

Vibratory ground motion and fault displacement hazards at Yucca Mountain have been analyzed probabilistically. Where and how often future earthquakes will occur, how large they will be, how much offset will occur at the earth's surface, and how ground motion will decay as a function of distance have been assessed. The input was developed by evaluating site data and analyzing other relevant information. To determine the probabilistic hazard for Yucca Mountain, uncertainties for each input were considered. The results are expressed as the annual frequency with which ground motion or fault displacement levels are exceeded.

A preliminary probabilistic study was carried out to support design of the Exploratory Studies Facility (CRWMS M&O 1994b). Ground motion hazard was determined for rock at the earth's surface. The results indicated ground motions of 265 cm per square second (0.27 g) and 647 cm per square second (0.66 g) are expected to be exceeded on average every 1,000 and 10,000 years, respectively. These ground motions have an annual frequency of being exceeded of $10^{-3}$ and $10^{-4}$, respectively.

This earlier analysis of seismic hazards was recently updated (USGS 1998). Two expert panels developed input to hazard calculations and considered more extensive site characterization results. To capture the full range of interpretations allowed by the data, the panels included scientists who participated in the actual site characterization studies and those who were independent of the studies. One panel, consisting of teams of geologists and seismologists from academia, government organizations, and the commercial world, characterized the sources of future earthquakes and their potential for surface fault displacement. The other panel consisted of ground motion seismologists from a similar range of backgrounds. This panel characterized ground motion and its attenuation for the Yucca Mountain region.

To determine ground motion and fault displacement hazard at Yucca Mountain, the experts' assessments were integrated along with their evaluations of uncertainties. For peak ground acceleration, results with a $10^{-3}$ and $10^{-4}$ annual frequency of being exceeded are, respectively, 165 and 523 cm per square second (0.169 and 0.534 g) for the horizontal component and 108 and 383 cm per square second (0.112 and 0.391 g) for the vertical component. These figures cannot be directly compared with earlier results because they were determined for a different reference location. Comparisons will be possible once site-specific soil and rock property data are obtained. These data can then be used to calculate final design ground motions. These results address the NRC subissue on seismic motion under the Structural Deformation and Seismicity Key Technical Issue (NRC 1997a) (see Volume 4, Section 4.3.3.2).

Probabilistic analysis based on the experts' assessments indicate that geologic fault displacement hazard is generally low. For sites not located on a major block-bounding fault, displacements greater than 0.1 cm (0.04 in.) will be exceeded on average less than once in 100,000 years. For this same time period, the mean displacements that are expected to be exceeded on two of the block-bounding faults—the Bow Ridge and Solitario Canyon faults—are 7.8 and 32 cm (3.1 and 13 in.), respectively. The primary design approach to mitigate fault displacement effects involves avoiding faults in laying out repository facilities. These results address the NRC subissue on fault slip under the Structural Deformation and Seismicity Key Technical Issue (NRC 1997a) (see Volume 4, Section 4.3.3.2).

The characterization of earthquake and fault hazard near Yucca Mountain is relatively mature. Future studies will provide site-specific information on soil and rock properties that will allow the seismic hazard results to be translated into inputs for seismic design analyses. In addition, seismic monitoring at Yucca Mountain will continue in order to confirm the results that have been obtained to date and to gather information on any nearby large events that occur in the future.

#### 2.2.7.3 Human Intrusion

Future explorers searching for economic resources could compromise the integrity of a waste repository at Yucca Mountain. The most likely exposure scenario would be from drilling operations that accidentally penetrate a waste package. Nevada is a major producer of nonfuel minerals, and the Southern Great Basin is a favorable geologic province for several types of economic deposits. Johnson and Hummel (1991) suggested that Yucca Mountain might contain economic resources. A combination of literature search, remote sensing, fieldwork, and petrographic and geochemical analyses were used to evaluate metallic resource potential at Yucca Mountain (CRWMS M&O 1998d). It was concluded that the potential repository area at Yucca Mountain contained no identifiable metallic mineral or uranium resources and had little or no potential for economically viable deposits in the foreseeable future.

Castor and Lock (1995) evaluated industrial minerals and rocks (e.g., barite, building stone, clay, construction aggregate, fluorite, limestone, pumice, silica, perlite, and zeolites) as potential resources at Yucca Mountain. Although several items in this category are known, or might be expected, to exist in or near the proposed repository area, these potential resources were judged to be uneconomic because of depth or material quality.

Neither outcrop, deep drillholes, or geophysical surveys have identified deposits of coal, oil shale, or tar-sands in the proposed repository area. Their potential as resources, therefore, is judged to be low (DOE 1988c, pp. 1-256–1-323). Geothermal resource potential in southern Nevada, including Yucca Mountain, is also judged to be very low (DOE 1988c, pp. 1-256–1-323).

Oil and gas resources are more difficult to evaluate because of their ability to migrate into permeable reservoir rock. However, the Nevada Bureau of Mines and Geology reviewed the oil and gas potential for the state and rated the oil potential as low for the region that includes Yucca Mountain (Garside et al. 1988). Grow et al. (1994) reviewed site-specific data for Yucca Mountain and also concluded that there was low potential for oil or gas in the region.

No economically viable resources have been identified. The characterization of resource potential at Yucca Mountain is nearly complete. Future work will focus on fully documenting the studies that have already been carried out. Results of these investigations address the NRC Key Technical Issue on Activities Related to Development of the U.S. Environmental Protection Agency Yucca Mountain Standard (NRC 1997a) (see Volume 4, Section 4.3.3).

## 3. REFERENCES

The numbers at the end of each reference are Office of Civilian Radioactive Waste Management document accession numbers. See the inside front cover of this document for whom to contact regarding more information.

### 3.1 DOCUMENTS CITED

Bandis, S.; Lumsden, A.C.; and Barton, N.R. 1983. "Fundamentals of Rock Joint Deformation." *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 20(6)*, 249–268. New York, New York: Pergamon Press. 224201.

Barnard, R.W.; Wilson, M.L.; Dockery, H.A.; Gauthier, J.H.; Kaplan, P.G.; Eaton, R.R.; Bingham, F.W.; and Robey, T.H. 1992. *TSPA 1991: An Initial Total-System Performance Assessment for Yucca Mountain.* SAND91-2795. Albuquerque, New Mexico: Sandia National Laboratories. NNA.19920630.0033.

Barr, D.L.; Moyer, T.C.; Singleton, W.L.; Albin, A.L.; Lung, R.C.; Lee, A.C.; Beason, S.C.; and Eatman, G.L. 1996 (unpublished). *Geology of the North Ramp—Stations 4+00 to 28+00, Exploratory Studies Facility, Yucca Mountain Project, Yucca Mountain, Nevada.* MS Report 366F60ZM. Denver, Colorado: USGS. MOL.19970106.0496.

Barton, C.A.; Hickman, S.; Morin, R; Zoback, M.D.; Finkbeiner, T.; Sass, J.; and Benoit, D., 1997. "Fracture Permeability and Its Relationship to In-Situ Stress in the Dixie Valley, Nevada, Geothermal Reservoir." *Proceedings from Twenty-Second Workshop on Geothermal Reservoir Engineering*, pp. 210–214. Palo Alto, California: Stanford University. 237673.

Barton, N.R.; Bandis, S; and Bakhtar, K. 1985. "Strength, Deformation, and Conductivity Coupling of Rock Joints." *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts.* New York, New York: Pergamon Press. *22(3)*, 121–140. 217135.

Bish, D.L. and Aronson, J.L. 1993. "Paleogeothermal and Paleohydrologic Conditions in Silicic Tuff from Yucca Mountain, Nevada." *Clays and Clay Minerals, 41*, 148–161. Long Island City, New York: Pergamon Press. 224613.

Bish, D.L., and Chipera, S.J. 1986. *Mineralogy of Drill Holes J-13 UE-25A#1, and USW G-1 at Yucca Mountain, Nevada.* Report LA-10764-MS. UC-70. Los Alamos, New Mexico: Los Alamos National Laboratory. MOL.19950412.0044.

Blair, S.C.; Berge, P.A.; and Wang, H.F. 1997. *Bounding Models for Estimating Changes in Fracture Permeability Due to Thermo-Mechanical Stresses in Host Rock Surrounding the Repository I: Permeability Changes Estimated for the Heated Drift Test.* Level 4 Milestone SPLF2M4, Yucca Mountain Project. Berkeley, California: Lawrence Livermore National Laboratory. MOL.19980107.0411.

Blanton, J.O., III. 1992. *Nevada Test Site Flood Inundation Study: Part of a Geological Survey Flood Potential and Debris Hazard Study, Yucca Mountain Site, for Department of Energy Office of Civilian Radioactive Waste Management.* Denver, Colorado: U.S. Bureau of Reclamation. 205029.

Bodvarsson, G.S. and Bandurraga, T.M., eds. 1996. *Development and Calibration of the Three-Dimensional Site-Scale Unsaturated Zone Model of Yucca Mountain, Nevada.* LBNL-39315. Berkeley, California: Lawrence Berkeley National Laboratory. MOL.19970701.0692.

Bodvarsson, G.S.; Bandurraga, T.M.; and Wu, Y.S., eds. 1997. *The Site-Scale Unsaturated Zone Model of Yucca Mountain, Nevada, for the Viability Assessment.* LBNL-40376, #UC-814. Berkeley, California: Lawrence Berkeley National Laboratory. MOL.19971014.0232.

Bredehoeft, J.D. 1997. "Fault Permeability near Yucca Mountain." *Water Resources Research, 33*, No. 11, 2459–2463. Washington, D.C.: American Geophysical Union. 236570.

Brocher, T.M.; Hunter, W.C.; and Langenheim, V.E. 1998. *Implications of Seismic Reflection and Potential Field Geophysical Data on the Structural Framework of the Yucca Mountain-Crater Flat Region, Nevada.* Geological Society of America Bulletin, 110, 947-971. Boulder, Colorado: Geologic Society of America. 238643.

Broxton, D.E.; Warren, R.G.; Hagan, R.C.; and Luedemann, G. 1986. *Chemistry of Diagenetically-Altered Tuffs at Potential Nuclear Waste Repository, Yucca Mountain, Nye County, Nevada.* LA-10802-MS. Los Alamos, New Mexico: Los Alamos National Laboratory. 202366.

Broxton, D.E.; Warren, R.G.; Byers, F.M.; and Scott, R.B. 1989. "Chemical and Mineralogic Trends Within the Timber Mountain-Oasis Valley Caldera Complex, Nevada: Evidence for Multiple Cycles of Chemical Evolution in a Long-Lived Silicic Magma System." *Journal of Geophysical Research, 94,* 5961–5985. Washington, D.C.: American Geophysical Union. 225928.

Broxton, D.E.; Chipera, S.J.; Byers, F.M.; and Rautman, C.A. 1993. *Geologic Evaluation of Six Nonwelded Tuff Sites in the Vicinity of Yucca Mountain, Nevada, for a Surface-Based Test Facility for the Yucca Mountain Project.* LA-12542-MS. UC-814. Los Alamos, New Mexico: Los Alamos National Laboratory. NNA.19940224.0128.

Bruton, C.J. 1995. *Testing EQ3/6 and GEMBOCHS Using Fluid-Mineral Equilibria in the Wairakei Geothermal System.* Letter Report, Milestone MOL206. Livermore, California: Lawrence Livermore National Laboratory. MOL.19960409.0131.

Buesch, D.C.; Spengler, R.W.; Moyer, T.C.; and Geslin, J.K. 1996. *Proposed Stratigraphic Nomenclature and Macroscopic Identification of Lithostratigraphic Units of the Paintbrush Group Exposed at Yucca Mountain, Nevada.* Open-File Report 94-469. Denver, Colorado: USGS. MOL.19970205.0061.

Bullard, K.L. 1986. *PMF (Probable Maximum Flood) Study for Nevada Nuclear Waste Storage Investigation Project.* Denver, Colorado: U.S. Bureau of Reclamation, Engineering and Research Center. NNA.19891019.0314.

Carey, J.W.; Chipera, S.J.; Vaniman, D.T.; Bish, D.L.; Viswanathan, H.S.; and Carter-Krogh, K. 1997. *Three-Dimensional Mineralogic Model of Yucca Mountain, Nevada.* Rev. 1.1, Draft R0. Los Alamos, New Mexico: Los Alamos National Laboratory. MOL.19980520.0170.

Castor, S.B. and Lock, D.E. 1995. *Assessment of Industrial Minerals in the Controlled Area.* Milestone Report UNLV99B. Reno, Nevada: Nevada Bureau of Mines and Geology. MOL.19980717.0139.

Chipera, S.J.; Bish, D.L.; and Carlos, B.A. 1995. "Equilibrium Modeling of the Formation of Zeolites in Fractures at Yucca Mountain, Nevada." *Natural Zeolites '93: Occurrence, Properties, Use.* Ming, D.W. and Mumpton, F.A. eds., 565–577. Brockport, New York: International Committee on Natural Zeolites. 217196.

Crowe, B.M.; Perry, F.V.; Valentine, G.A.; Wallmann, P.C.; and Kossik, R. 1993. "Simulation Modeling of the Probability of Magmatic Disruption of the Potential Repository Yucca Mountain Site." *Proceedings of the Topical Meeting on Site Characterization and Model Validation Focus '93 September 26-29, 1993, Las Vegas, Nevada,* 182–191. La Grange Park, Illinois: American Nuclear Society. 225003.

Crowe, B.; Perry, F.; Geissman, J.; McFadden, L.; Wells, S.; Murrell, M.; Poths, J.; Valentine, G.A.; Bowker, L.; and Finnegan, K. 1995. *Status of Volcanism Studies for the Yucca Mountain Site Characterization Projects.* LA-12908-MS. UC-802. Los Alamos, New Mexico: Los Alamos National Laboratory. MOL.19951127.0106.

CRWMS (Civilian Radioactive Waste Management System) M&O (Management and Operating Contractor) 1994a. *Total System Performance Assessment-1993: An Evaluation of the*

*Potential Yucca Mountain Repository.* B00000000-01717-2200-00099 REV 01. Las Vegas, Nevada: CRWMS M&O. NNA.19940406.0158.

CRWMS M&O 1994b. *Seismic Design Inputs for the Exploratory Studies Facility at Yucca Mountain.* BAB000000-01717-5705-00001 REV 02. Las Vegas, Nevada: CRWMS M&O. MOL.19951018.0040.

CRWMS M&O 1995. *Total System Performance Assessment–1995: An Evaluation of the Potential Yucca Mountain Repository.* B00000000-01717-2200-00136 REV 01. Las Vegas, Nevada: CRWMS M&O. MOL.19960724.0188.

CRWMS M&O 1996a. *Mined Geologic Disposal System Advanced Conceptual Design Report.* B00000000-01717-5705-00027 REV 00. Las Vegas, Nevada: CRWMS M&O. MOL.19960826.0094, MOL.19960826.0095, MOL.19960826.0096, MOL.19960826.0097.

CRWMS M&O 1996b. *Probabilistic Volcanic Hazard Analysis for Yucca Mountain, Nevada.* BA0000000-01717-2200-00082 REV 00. Las Vegas Nevada: CRWMS M&O. MOL.19961119.0034.

CRWMS M&O 1997a. *Engineering Design Climatology and Regional Meteorological Conditions Report.* B00000000-01717-5707-00066 REV 00. Las Vegas, Nevada: CRWMS M&O. MOL.19980304.0028.

CRWMS M&O 1997b. *Performance Confirmation Plan.* B00000000-00841-4600-00002 REV 00. Las Vegas, Nevada: CRWMS M&O. MOL.19980204.1022.

CRWMS M&O 1997e. *ISM2.O: A 3 D Geologic Framework and Integrated Site Model of Yucca Mountain.* B00000000-01717-5700-0004 REV 00. Las Vegas, Nevada: CRWMS M&O. MOL.19970625.0119.

CRWMS M&O 1997f. *Determination of Available Volume for Repository Siting.* BCA000000-01717-0200-00007 REV 00. Las Vegas, Nevada: CRWMS M&O. MOL.19971009.0699.

CRWMS M&O 1997g. *Repository Thermal Loading Analysis.* B00000000-01717-0200-00135 REV 00. Las Vegas, Nevada: CRWMS M&O. MOL.19971201.0601.

CRWMS M&O 1998a. *Near-Field/Altered-Zone Models Report.* UCRL-ID-129179. Milestone Report SP3100M3. Las Vegas, Nevada: CRWMS M&O. MOL.19980630.0560.

CRWMS M&O 1998d. *Yucca Mountain Site Description.* B00000000-01717-5700-00019, REV 00. Las Vegas, Nevada: CRWMS M&O.

Section 1-Geography and Demography. MOL.19980729.0047.

Section 2-Nearby Industrial, Transportation, and Military Facilities. MOL.19980729.0048.

Section 3-Geology. MOL19980729.0049.

Section 4-Climatology and Meterology. MOL.19980729.0050.

Section 5-Hydrologic System. MOL.19980729.0051.

Section 6-Geochemistry. MOL.19980729.0052.

Section 7-Integrated Natural System Response to Thermal Loading. MOL.19980729.0053.

D'Agnese, F.A.; Faunt, C.C.; Turner, A.K.; and Hill, M.C. 1997a. *Hydrogeologic Evaluation and Numerical Simulation of the Death Valley Regional Ground-Water Flow System, Nevada and California.* Water-Resources Investigations Report USGS-WRIR 96-4300. Denver, Colorado: USGS. MOL.19980306.0253.

D'Agnese, F.A.; O'Brien, G.M.; Faunt, C.C.; and San Juan, C.A. 1997b (unpublished). *Regional*

*Saturated-Zone Synthesis Report—Simulated Effects of Climate Change on the Death Valley Regional Ground-Water Flow System, Nevada and California.* Milestone Report SP23OM3. Water-Resources Investigations Report. Denver, Colorado: USGS. MOL.19980130.0211.

Day, W.C.; Dickerson, R.P., Potter, C.J.; Sweetkind, D.S.; San Juan, C.A.; Drake, R.M. II; and Fridrich, C.J. 1997. *Bedrock Geologic Map of the Yucca Mountain Area, Nye County, Nevada.* Administrative Report. Denver, Colorado: USGS. MOL.19980310.0122.

Day, W.C.; Dickerson, R.P.; Potter, C.J.; Sweetkind, D.S.; San Juan, C.A.; Drake, R.M. II; and Fridrich, C.J. 1998. *Bedrock Geologic Map of the Yucca Mountain Area, Nye County, Nevada.* USGS Geologic Investigations Map I-2627. Denver, Colorado: USGS. 238732.

Delany, J.M. 1985. *Reaction of Topopah Spring Tuff with J-13 Water: A Geochemical Modeling Approach Using the EQ3/6 Reaction Path Code.* UCRL-53631. Livermore, California: Lawrence Livermore National Laboratory. HQS.19880517.2419.

Diehl, S.F. and Chornack, M.P. 1990. *Stratigraphic Correlation and Petrography of the Bedded Tuffs, Yucca Mountain, Nye County, Nevada.* Open-File Report 89-3. Denver, Colorado: USGS. NNA.19901102.0006.

DOE (U.S. Department of Energy) 1980. *Final Environmental Impact Statement Management of Commercially Generated Radioactive Waste.* DOE/EIS-0046F. Washington, D.C.: OCRWM. 205022.

DOE 1986a. *Nuclear Waste Policy Act (Section 112) - Environmental Assessment: Yucca Mountain Site, Nevada Research and Development Area, Nevada.* DOE/RW-0073, pp.2-15. Las Vegas, Nevada: YMSCO. HQZ.19870302.0332.

DOE 1986b. *Recommendation by the Secretary of Energy of Candidate Sites for Site Characterization for the First Radioactive-Waste Repository.* DOE/S-0048. Washington, D.C.: OCRWM. MOL.19980701.0391.

DOE 1987. *Mission Plan Amendment for the Office of Civilian Radioactive Waste Management.* DOE/RW-0128. Las Vegas, Nevada: YMSCO. HQS.19880517.0935.

DOE 1988c. *Site Characterization Plan, Yucca Mountain Site, Nevada Research and Development Area, Nevada.* DOE/RW-0199. Las Vegas, Nevada: YMSCO. HQO.19881201.0002.

DOE 1994. *Civilian Radioactive Waste Management Program Plan.* DOE/RW-0458 REV 01, Draft. Washington D.C.: OCRWM. HQO.19941222.0001, HQO.19941222.0002, and HQO.19941222.0003.

DOE 1996. *Civilian Radioactive Waste Management Program Plan.* DOE/RW-0458 REV 1, Draft. Las Vegas, Nevada: YMSCO. HQO.19960314.0001.

DOE 1998. *Repository Safety Strategy: U.S. Department of Energy's Strategy to Protect Public Health and Safety After Closure of a Yucca Mountain Repository.* YMP/96-01, REV 02. Washington, D.C.: OCRWM. MOL.19980727.0001.

Fabryka-Martin, J.T.; Flint, A.L.; Sweetkind, D.S.; Wolfsberg, A.V.; Levy, S.S.; Roemer, G.J.C.; Roach, J.L.; Wolfsberg, L.E.; and Duff, M.C. 1997a. *Evaluation of Flow and Transport Models of Yucca Mountain, Based on Chlorine-36 Studies for FY 97.* LA-CST-TIP-97-010. Los Alamos, New Mexico: Los Alamos National Laboratory. MOL.19980204.0916.

Fabryka-Martin, J.T.; Wolfsberg, A.V.; Dixon, P.R.; Levy, S.S.; Musgrave, J.; and Turin, H.J. 1998. *Summary Report of Chlorine-36 Studies: Sampling, Analysis and Simulation of Chlorine-36 in the Exploratory Studies Facility.* LA-13352-MS. Los Alamos, New Mexico: Los Alamos National Laboratory. MOL.19980812.0254.

Faunt, C.C. 1997. *Effect of Faulting on Ground-Water Movement in the Death Valley Region, Nevada and California.* Water-Resources Investigations Report USGS-WRIR-95-4132. Denver, Colorado: USGS. MOL.19980429.0119.

Flint, L.E. and Flint, A.L. 1995. *Shallow Infiltration Processes at Yucca Mountain, Nevada--Neutron Logging Data 1984-93.* Water-Resources Investigations Report USGS-WRIR-95-4035. Denver, Colorado: USGS. MOL.19960924.0577.

Flint, A.L.; Hevesi, J.A.; and Flint, L.E. 1996 (unpublished). *Conceptual and Numerical Model of Infiltration for the Yucca Mountain Area, Nevada.* Draft. Denver, Colorado: USGS. MOL.19970409.0087.

Flint, L.E. 1998. *Characterization of Hydrogeologic Units Using Matrix Properties, Yucca Mountain, Nevada.* Water-Resources Investigations Report USGS-WRIR-97-4243. Denver, Colorado: USGS. 236515.

Forester, R.M.; Bradbury, J.P.; Carter, C.; Elvidge, A.; Hemphill, M.; Lundstrom, S.C.; Mahan, S.A.; Marshall, B.D.; Neymark, L.A.; Paces, J.B.; Sharpe, S.; Whelan, J.F.; and Wigand, P. 1996. *Synthesis of Quaternary Response of the Yucca Mountain Unsaturated and Saturated Zone Hydrology to Climate Change.* Milestone Report 3GCA102M. Denver, Colorado: USGS. MOL.19970211.0026.

Garside, L.J.; Hess, R.H.; Fleming, K.L.; and Weimer, B.S. 1988. "Oil and Gas Developments in Nevada." *Nevada Bureau of Mines and Geology Bulletin 104.* Reno, Nevada: Nevada Bureau of Mines and Geology. 214106.

Gnanapragasam, E.K. and Lewis, B.G. 1995. "Elastic Strain Energy and the Distribution Coefficient of Radium in Solid Solutions and Calcium Salts." *Geochimica et Cosmochimica Acta, 59,* 5103–5111. New York, New York: Pergamon Press. 236660.

Grow, J.A.; Barker, C.E.; and Harris, A.G. 1994. "Oil and Gas Exploration near Yucca Mountain, Nevada." *High-Level Radioactive Waste Management: Proceedings of the Fifth Annual International Conference, Las Vegas, Nevada, May 22-26, 1994, 3,* 1298–1315. La Grange Park, Illinois: American Nuclear Society. 238655.

Hamilton, W.B. 1988. "Detachment Faulting in the Death Valley Region, California and Nevada," in *Geologic and Hydrologic Investigations of a Potential Nuclear Waste Disposal Site at Yucca Mountain, Southern Nevada.* U.S. Geological Survey Bulletin 1790, 51–85. Denver, Colorado: USGS. 218245.

Hauge, T.A.; Allmendinger, R.; Caruso, C.; Hauser, E.; Klemperer, S.; Opdyke, S.; Potter, C.; Sanford, W.; Brown, L.; Kaufman, S.; and Oliver, J. 1987. "Crustal Structure of Western Nevada from COCORP Deep Seismic-Reflection Data." *Geological Society of America Bulletin, 98,* 320–329. Boulder, Colorado: Geological Society of America. 234449.

Hill C.A.; Dublyansky, Y.V.; Harmon, R.S.; and Schluter, C.M. 1995. "Overview of Calcite/Opal Deposits at or Near the Proposed High-Level Nuclear Waste Site, Yucca Mountain, Nevada, Pedogenic, Hypogene, or Both?" *Environmental Geology, 26,* 69–88. New York, New York: Springer International. 234728.

Houghton, J.G.; Gifford, R.D.; and Sakamoto, C.M. 1975. *Nevada's Weather and Climate.* Special Publications No. 2. Reno, Nevada: Nevada Bureau of Mines and Geology. 225666.

International Agency for Research on Cancer 1997. *Silica, Some Silicates, Coal Dust and Para-Aramid Fibrilss: IARC Monographs on the Evaluation of the Carcinogenic Risk of Chemicals to Humans.* Volume 68. Lyon, France: World Health Organization, International Agency for Research on Cancer. 236833.

Imbrie, J.; Hays, J.D.; Martinson, D.G.; McIntrye, A.; Mix, A.C.; Morley, J.J.; Pisias, N.G.; Prell, W.L.; and Shackleton, N.J. 1984. "The Orbital Theory of Pleistocene Climate: Support from a Revised Chronology of the Marine 18-0 Record."

*Milankovich and Climate,* 269-305. Berger, A.L.; Imbrie, J.; Kukla, G.; and Saltzman, B., eds. Boston, Massachusetts: D. Reidel Publishing Company. 225740.

Interagency Review Group on Nuclear Waste Management 1979. *Report to the President by the Interagency Review Group on Nuclear Waste Management.* TID-29442. Washington D.C.: DOE. MOL.19980625.0169.

Itasca Consulting Group Inc. 1996. *FLAC, Fast Lagrangian Analysis of Continua.* Version 3.3, Vol. I-IV, Users' Manuals. Minneapolis, Minnesota: Itasca Consulting Group, Inc. 236418, 236419, 236420, 236421.

Johnson, C. and Hummel, P. 1991. "Yucca Mountain, Nevada - Nuclear Waste or Resource Rich." *Geotimes 36 (8),* 14–16. Falls Church, Virginia: American Geophysical Institute. 234741.

Knauss, K.G.; Peifer, D.; Piwinskii A.; and Beiriger, W.J. 1985. *Hydrothermal Interaction of Solid Wafers of Topopah Spring Tuff with J-13 Water and Distilled Water at 90°C, 150°C, and 250°C Using Dickson-Type, Gold-Bag Rocking Autoclaves.* UCRL-53645. Livermore, California: Lawrence Livermore National Laboratory. NNA.19900207.0282.

Knauss, K.G. and Peifer, D.W. 1986. *Reaction of Vitric Topopah Spring Tuff and J-13 Groundwater under Hydrothermal Conditions Using Dickson-Type, Gold-Bag Rocking Autoclaves.* UCRL-53795. Livermore, California: Lawrence Livermore National Laboratory. NNA.19891102.0117.

Knauss, K.G.; Beiriger, W.J.; and Peifer, D.W. 1987. *Hydrothermal Interaction of Solid Wafers of Topopah Spring Tuff with J-13 Water at 90 and 150°C Using Dickson-Type, Gold-Bag Rocking Autoclaves: Long-Term Experiments.* UCRL-53722. Livermore, California: Lawrence Livermore National Laboratory. NNA.19870713.0081.

Knauss, K.G. 1987. "Zeolitization of Glassy Topopah Spring Tuff under Hydrothermal Conditions." *Materials Research Society Symposium Proceedings 84,* 737–745. Pittsburgh, Pennsylvania: Materials Research Society. 223724.

Langmuir, D. 1997. *Aqueous Environmental Geochemistry.* Upper Saddle River, New Jersey: Prentice Hall. 237107.

LeCain, G.D. 1997. *Air-Injection Testing in Vertical Boreholes in Welded and Nonwelded Tuff, Yucca Mountain, Nevada.* Water-Resources Investigations Report USGS-WRIR-96-4262. Denver, Colorado: USGS. MOL.19980310.0148.

LeCain, G.D. and Patterson, G.L. 1997. *Technical Analysis and Interpretation: ESF Air-Permeability and Hydrochemistry Data Through January 31, 1997.* Letter Report to Technical Project Officer (March 11, 1997). Milestone SPH35EM4. Denver, Colorado: USGS. 238551.

LeCain, G.D.; Patterson, G.L.; and Severson, G.R. 1997 (unpublished). *Results From Pneumatic Monitoring, Hydrochemistry Sampling, Air-Injection, and Tracer Testing in the Upper Tiva Canyon, and Bow Ridge Fault Alcoves, Yucca Mountain, Nevada, November, 1994 to July, 1996.* Milestone Report 3GUS619M. Denver, Colorado: USGS. MOL.19970415.0387.

LeCain, G.D. 1998. *Results from Air-Injection and Tracer Testing in the Upper Tiva Canyon, Bow Ridge Fault and Upper Paintbrush Contact Alcoves of the Exploratory Studies Facility, August 1994 Through July 1997, Yucca Mountain, Nevada.* Water Resources Investigations Report USGS-WRIR-98-4058. Denver, Colorado: USGS. 237249

Lee, K.H., and Ueng, T.S. 1991. *Air-Injection Field Tests to Determine the Effect of a Heat Cycle on the Permeability of Welded Tuff.* UCRL-ID-105163. Livermore, California: Lawrence Livermore National Laboratory. NNA.19910912.0001.

Levy, S.S. 1991. "Mineralogic Alteration History and Paleohydrology at Yucca Mountain, Nevada." *High-Level Radioactive Waste Management: Proceedings of the Second Annual International Conference, Las Vegas, Nevada, April 28-May 3, 1991.* La Grange Park, Illinois: American Nuclear Society. 217642.

Li, J.; Lowenstein, T.K.; Brown, C.B.; Ku, T-L.; and Luo, S. 1995. "A 100 Karecord of Water Tables and Paleoclimates from Salt Cores, Death Valley, California." *Palaeogeography, Palaeoclimatology, Palaeoecology 123*, 179–203. Amsterdam, Netherlands: Elsevier. 236544.

Luckey, R.R; Tucci, P.; Faunt, C.C.; Ervin, E.M.; Steinkampf, W.C.; D'Agnese, F.A.; and Patterson, G.L. 1996. *Status of Understanding of the Saturated-Zone Ground-Water Flow System at Yucca Mountain, Nevada, as of 1995.* Water-Resources Investigations Report USGS-WRIR-96-4077. Denver, Colorado: USGS. 227084.

Mansure, A.J. and Ortiz, T.S. 1984. *Preliminary Evaluation of the Subsurface Area Available for a Potential Nuclear Waste Repository at Yucca Mountain.* SAND84-0175. Albuquerque, New Mexico: Sandia National Laboratories. NNA.19870407.0047.

Marshall, B.D.; Futa, K.; and Peterman, Z.E. 1997. "Hydrologic Inferences from Strontinum Isotopes in Pore Water from the Unsaturated Zone at Yucca Mountain, Nevada." *EOS: Transactions, American Geophysical Union, 78,* F308. Washington, D.C.: American Geophysical Union. 237795.

Martin, R.J.; Price, R.H.; Boyd, P.J.; and Noel, J.S. 1995. *Creep in Topopah Spring Member Welded Tuff.* SAND94-2585. Albuquerque, New Mexico: Sandia National Laboratories. MOL.19950502.0006.

Martin, R.J.; Noel, J.S.; Boyd, P.J.; and Price, R.H. 1996. "Thermal Expansion as a Function of Confining Pressure for Welded Tuff from Yucca Mountain." *Rock Mechanics Tools and Techniques.* Proceedings from 2nd North American Rock Mechanics Symposium, NARMS '96,. A regional Conference of ISRM/Montreal/ Quebec/Canada, 19-21 June 1996. Montreal, Canada. Rotterdam, Netherlands: A.A. Balkema. 237844.

Matyskiela, W. 1997. "Silica Redistribution and Hydrologic Changes in Heated Fractured Tuff." *Geology 25(12),* 1115–1118. Boulder, Colorado: Geologic Society of America. 236809.

McKinley, P.W.; Long, M.P.; and Benson, L.V. 1991. *Chemical Analyses of Water from Selected Wells and Springs in the Yucca Mountain Area, Nevada, and Southeastern California.* Open-File Report 90-355. Denver, Colorado: USGS. NNA.19901031.0004.

Montazer, P. and Wilson, W.E. 1984. *Conceptual Hydrologic Model of Flow in the Unsaturated Zone, Yucca Mountain, Nevada.* Water-Resources Investigation Report USGS-WRIR-84-4345. Denver, Colorado: USGS. NNA.19890327.0051.

Moyer, T.C.; Geslin, J.K.; and Flint, L.E. 1996. *Stratigraphic Relations and Hydrologic Properties of the Paintbrush Tuff Nonwelded (PTn) Hydrologic Unit, Yucca Mountain, Nevada.* Open-File Report USGS-OFR-95-397. Denver, Colorado: USGS. MOL.19970204.0216.

Murray, R.L. 1994. *Understanding Radioactive Waste*, 4th ed. Columbus, Ohio: Battelle Press. 226776.

National Research Council, Committee on Waste Disposal 1957. *The Disposal of Radioactive Waste on Land.* National Research Council Publication 519. Washington D.C.: National Academy of Sciences/National Research Council. 221455.

National Research Council 1990. *Rethinking High-Level Radioactive Waste Disposal.* Washington, D.C.: National Academy Press. 205153.

National Research Council 1992. *Ground Water at Yucca Mountain: How High Can It Rise?, Final Report of the Panel on Coupled/Hydrologic/*

*Tectonic/Hydrothermal Systems at Yucca Mountain.* Washington, D.C.: National Academy Press. 238347.

National Research Council 1995. *Technical Bases for Yucca Mountain Standards.* Washington, D.C.: National Academy Press. 104273.

Nevada State Demographer 1998a (February 24). *Population of Nevada's Counties and Incorporated Cities, Population Estimates-State, Counties, Incorporated Cities, and Unincorporated Towns.* Reno, Nevada: Nevada Department of Taxation. 237862.

Nevada State Demographer 1998b (February 24). *Population of Nevada's Unincorporated Towns, Population Estimates-State, Counties, Incorporated Cities, and Unincorporated Towns.* Reno, Nevada: Nevada Department of Taxation. 237863.

Nitsche, H.; Roberts, K.; Prussin, T.; Muller, A.; Becraft, K.; Keeney, D.; Carpenter, S.A.; Gatti, R.C. 1994. *Measured Solubilities and Speciations from Oversaturation Experiments of Neptunium, Plutonium, and Americium in UE-25 P#1 Well Water from the Yucca Mountain Region.* LA-12563-MS. Los Alamos, New Mexico: Los Alamos National Laboratory. MOL.19951006.0171.

Nitsche, H.; Roberts, K.; Becraft, K.; Prussin, T.; Keeney, D.; Carpenter, S.A.; and Hobart, D.E. 1995. *Solubility and Speciation Results from Over- and Undersaturation Experiments on Neptunium, Plutonium, and Americium in Water from Yucca Mountain Region Well UE-25p #1.* LA-13017-MS. Los Alamos, New Mexico: Los Alamos National Laboratory. MOV.19980501.0078.

Nolting, R. and Sun, Y. 1997. *Summary/Workshop on Significant Issues and Available Data "Near-Field/Altered Zone Coupled Effects" Expert Elicitation Project Drift Scale Thermomechanical Analysis.* Las Vegas, Nevada: Morrison-Knudsen/ CRWMS M&O. MOL.19980619.0639.

NRC (Nuclear Regulatory Commission) 1977. Regulatory Guide 1.109: *Calculation Of Annual Doses To Man From Routine Releases Of Reactor Effluents For The Purpose Of Evaluating Compliance With 10 CFR Part 50, Appendix I.* Washington, D.C.: NRC. 222641.

NRC 1997a. *NRC High-Level Radioactive Waste Program Annual Progress Report: Fiscal Year 1996.* NUREG/CR-6513, No. 1. Washington, D.C.: NRC. 232063.

NRC 1998. "Development of a New 10 CFR Part 63." Section III in *Proposed Rule for Disposal of High-Level Radioactive Wastes in a Proposed Geologic Repository at Yucca Mountain, Nevada* [Online]. NRC. Available: http://techconf.llnl.gov/cgi-bin/library?source=html&library=pt63_yucca_lib&file =026-0002.htm [November 25, 1998]. Washington, D.C.: NRC. 241340.

Nuclear Waste Technical Review Board 1998. Letter Report to L.H. Barrett, Acting Director, Office of Civilian Radioactive Waste Management. Subject: Board Review of 11 Reports Submitted by Mr. Jerry Szymanski. Arlington, Virginia: Nuclear Waste Technical Review Board. MOL.19980814.0396.

Oliver, T. and Root, T. 1997 (unpublished). *Hydrochemical Database for the Yucca Mountain Area, Nye County, Nevada.* Milestone Report SPH34BM4. Denver, Colorado: USGS. 238148.

Olsson, W.A. and Brown, S.R. 1994. *Mechanical Properties of Seven Fractures from Drillholes NRG-4 and NRG-6 at Yucca Mountain, Nevada.* SAND94-1995. UC-814. Albuquerque, New Mexico: Sandia National Laboratories. MOL.19941007.0081.

Pabst, M.E., Beck, D.A.; Glancy, P.A.; and Johnson, J.A. 1993. *Streamflow and Selected Precipitation Data for Yucca Mountain and Vicinity, Nye County, Nevada, Water Years 1983-85.* Open-File Report USGS-OFR-93-438. Carson City, Nevada: USGS. MOL.19950104.0204.

Paces, J.B.; Neymark, L.A.; Marshall, B.D.; Whelan, J.F.; and Peterman, Z.E. 1996b. *Ages and Origins of Subsurface Secondary Minerals in the*

*Exploratory Studies Facility (ESF).* Milestone Report 3GQH450M. Denver, Colorado: USGS. MOL.19970324.0052.

Paces, J.B.; Marshall, B.D.; Whelan, J.F.; and Neymark, L.A. 1997 (unpublished). *Progress Report on Unsaturated Zone Stable and Radiogenic Isotope Studies.* Milestone Report SPC23FM4. Denver, Colorado: USGS. 238068.

Paces, J.B.; Ludwig, K.R.; Peterman, Z.E.; Neymark, L.A; and Kenneally, J.M. 1998. "Anomalous Groundwater $^{234}U/^{238}U$ Beneath Yucca Mountain: Evidence of Local Recharge?" *High-Level Radioactive Waste Management: Proceedings of the Eighth Annual International Conference, Las Vegas, Nevada, May 11-14, 1998.* La Grange Park, Illinois: American Nuclear Society. 237806.

Patterson, G.L.; Weeks, E.P.; Rousseau, J.P.; and Oliver, T.A. 1996 (unpublished). *Interpretation of Pneumatic and Chemical Data From the Unsaturated Zone Near Yucca Mountain, Nevada.* Milestone Report 3GGP605M. Denver, Colorado: USGS. MOL.19970324.0058.

Peterman, Z.E. and Stuckless, J.S. 1993. "Applications of Strontium and Other Radiogenic Tracer Isotopes to Paleohydrology Studies." *Proceedings for A Workshop on Paleohydrological Methods and Their Applications for Radioactive Waste Disposal,* 59–84. Paris, France: Nuclear Energy Agency. 238760.

Price, R.H.; Connolly, J.R.; and Keil, K. 1987. *Petrologic and Mechanical Properties of Outcrop Samples of the Welded, Devitrified Topopah Spring Member of the Paintbrush Tuff.* SAND86-1131. Albuquerque, New Mexico: Sandia National Laboratories. NNA.19870601.0013.

Quade, J., and Cerling, T.E. 1990. "Stable Isotopic Evidence for a Pedogenic Origin of Carbonates in Trench 14 Near Yucca Mountain, Nevada." *Science, 250,* 1549–1552. Washington, D.C.: American Association for the Advancement of Science. 222617.

Quade, J.; Mifflin, M.D.; Pratt, W.L.; McCoy, W.; and Burckle, L. 1995. "Fossil Spring Deposits in the Southern Great Basin and their Implications for Changes in Water-Table Levels Near Yucca Mountain, Nevada, During Quaternary Time." *Geologic Society of America Bulletin, 107(2),* 213–230. Boulder, Colorado: Geological Society of America. 234256.

Robinson, B.A.; Wolfsberg, A.V.; Viswanathan, H.S.; Bussod, G.Y.; Gable, C.W.; and Meijer, A. 1997. *The Site-Scale Unsaturated Zone Transport Model of Yucca Mountain.* Milestone SP25BM3, Rev. 1. Los Alamos, New Mexico: Los Alamos National Laboratory. MOL.19980203.0570.

Robinson, B.A.; Wolfsberg, A.V.; Viswanathan, H.S.; Gable, C.W.; Zyvoloski, G.A.; and Turin, H.J. 1996. *Site Scale Unsaturated Zone Flow and Transport Model: Modeling of Flow, Radionuclide Migration, and Environmental Isotope Distributions at Yucca Mountain.* Milestone Report 3672. Draft. Los Alamos, New Mexico: Los Alamos National Laboratory. MOL.19971111.0625.

Rogers, A.M.; Harmsen, S.C.; and Meremonte, M.E. 1987. *"Evaluation of the Seismicity of Southern Great Basin and Its Relationship to the Tectonic Framework of the Region."* Open-File Report 87-408. Denver, Colorado: USGS. MOL.19980330.0439.

Rousseau, J.P.; Kwicklis, E.M.; and Gillies, D.C., eds., 1996. *Hydrogeology of the Unsaturated Zone, North Ramp Area of the Exploratory Studies Facility, Yucca Mountain, Nevada.* Draft Milestone Report 3GUP431M. Denver, Colorado: USGS. MOL.19980223.0574, MOL.19980220.0164. (Final Report to be published as Water-Resources Investigations Report 98-4050.)

Rousseau, J.P.; Loskot, C.L.; Thamir, F.; and Lu, N. 1997. *Results of Borehole Monitoring in the Unsaturated Zone Within the Main Drift Area of the Exploratory Studies Facility, Yucca Mountain, Nevada.* Milestone Report SPH22M3. Denver, Colorado: USGS. MOL.19970626.0351.

Sandia National Laboratories. 1984. *Site Characterization Plan-Conceptual Design Report.* SAND84-2641. Albuquerque, New Mexico. Sandia National Laboratories. NN1.19880902.0014, NN1.19880902.0015, NN1.19880902.0016, NN1.19880902.0017, NN1.19880902.0018, NN1.19880902.0019.

Sass, J.H.; Dudley, W.W. Jr.; and Lachenbruch, A.H. 1995. *Major Results of Geophysical Investigations at Yucca Mountain and Vicinity, Southern Nevada.* Oliver, H.W.; Ponce, D.A.; and Hunter, W.C., eds. Open-File Report OFR-95-74. Denver, Colorado: USGS. MOL.19980305.0122.

Sawyer, D.A.; Fleck, R.J.; Lanphere, M.A.; Warren, R.G.; Broxton, D.E.; and Hudson, M.R. 1994. "Episodic Caldera Volcanism in the Miocene Southwestern Nevada Volcanic Field: Revised Stratigraphic Framework, 40Ar/39Ar Geochronology, and Implications for Magmatism and Extension." *Geological Society of America Bulletin 106,* 1304–1318. Boulder, Colorado: Geological Society of America. 222523.

Schelling, F.J. and Thompson, S.L., 1997. *Future Climate Modeling Scenarios.* Milestone Report SLTR97-0001. Las Vegas, Nevada: CRWMS M&O. MOL.19971021.0607.

Schneider, J.F.; Abrahamson, N.A.; and Hanks, T.C. 1996. *Yucca Mountain Project, Ground Motion Modeling of Scenario Earthquakes at Yucca Mountain.* Final Report For Activity 8.3.1.17.3.3. Las Vegas, Nevada: Woodward-Clyde Federal Services. 238153.

Smith, G.I. and Bischoff, J.L. 1997. "Core OL-92 from Owens Lake: Project Rationale, Geologic Setting, Drilling Procedures, and Summary." *An 800,000-Year Paleoclimatic Record from Core OL-92.* Smith, G.I., and Bischoff, J.L., eds. Special Paper 317, 1–8. Boulder, Colorado: U.S. Geological Society of America. 237295.

Spaulding, W.G. 1990. "Vegetational and Climatic Development of the Mojave Desert: The Last Glacial Maximum to the Present." *Packrat Middens: The Last 40,000 Years of Biotic Change.* Betancourt, J.L.; Van Devender, T.R.; and Martin, P.S., eds. Tucson Arizona: The University Press. 166-199. 234344.

Spudich, P.; Fletcher, J. B.; Hellweg, M.; Boatwright, J.; Sullivan, C.; Joyner, W. B.; Hanks, T.C.; Boore, D.M.; McGarr, A.; Baker, L.M.; and Lindh, A.G. 1997. "SEA-96 – A New Predictive Relation for Earthquake Ground Motions in Extensional Tectonic Regimes." *Seismological Research Letters, 68,* 190-198. Boulder, Colorado: WICHE Printing Services for ESSSA (Eastern Section-Seismological Society of America). 234935.

Stewart, J.H. 1988. "Tectonics of the Walker Lane Belt, Western Great Basin - Mesozoic and Cenozoic Deformation in a Zone of Shear." *Metamorphism and Crustal Evolution of the Western United States, VII,* 684–713. Ernst, W.G., ed. Englewood Cliffs, New Jersey: Prentice-Hall, Inc. 218183.

Striffler, P.; O'Brien, G.M.; Oliver, T.; and Burger, P. 1996. *Perched Water Characteristics and Occurrences, Yucca Mountain, Nevada.* Milestone Report 3GUS600M. Denver, Colorado: USGS. 238151.

Stuckless, J.S.; Marshall, B.D.; Vaniman, D.T.; Dudley, W.W.; Peterman, Z.E.; Paces, J.B.; Whelan, J.F.; Taylor, E.M.; Forester, R.M.; and O'Leary, D.W. 1998. "Comments on 'Overview of Calcite/Opal Deposits at or Near the Proposed High-Level Nuclear Waste Site, Yucca Mountain, Nevada, USA: Pedogenic, Hypogene, or Both' by C.A. Hill, Y.V. Dublansky, R.S. Harmon, and C.M. Schluter." *Environmental Geology, 34(1),* 70-78. New York, New York: Springer Verlag. 238097.

Su, F.; Anderson, J.G.; Brune, J.N.; and Yuehua Z. 1996. "A Comparison of Direct S-Wave and Coda Wave Site Amplification Determined from Aftershocks of the Little Skull Mountain Earthquake." *Bulletin of the Seismological Society of America, 86(4),* 1006–1018. El Cerrito, California: Seismological Society of America. 236585.

Sweetkind, D.S. and Williams-Stroud, S. 1996. *Characteristics of Fractures at Yucca Mountain,* *Nevada: Synthesis Report.* Denver, Colorado: USGS. MOL.19961213.0181.

Sweetkind, D.S.; Barr, D.L; Polacsek, D.K.; and Anna, L.O. 1997. *Integrated Fracture Data in Support of Process Models, Yucca Mountain, Nevada.* Milestone Report SPG32M3. Denver, Colorado: USGS. MOL.19971017.0726.

Szabo, B.J.; Kolesar, P.T.; Riggs, A.C.; Winograd, I.J.; and Ludwig, K.R. 1994. "Paleoclimatic Inferences from a 120,000-Yr Calcite Record of Water-Table Fluctuation in Browns Room of Devils Hole, Nevada." *Quaternary Research, 41,* 59–69. New York, New York: Academic Press. 234642.

Szymanski, J.S. 1987. *Conceptual Considerations of the Death Valley Groundwater System with Special Emphasis on the Adequacy of This System to Accommodate the High-Level Nuclear Waste Repository (Draft).* DOE Internal Report. Las Vegas Nevada: YMSCO. NN1.19881122.0086.

Szymanski, J.S. 1989. *Conceptual Considerations of the Yucca Mountain Groundwater System with Special Emphasis on the Adequacy of This System to Accommodate a High-Level Nuclear Waste Repository.* DOE Internal Report. Las Vegas, Nevada: YMSCO. NNA.19890831.0152.

Tsang, C.F.; Birkholzer, J.; Li, G.; and Tsang, Y. 1997. *Drift Scale Modeling: Progress in Studies of Seepage into a Drift.* Milestone Report SP331CM4. Berkeley, California: Lawrence Berkeley National Laboratory. MOL.19971204.0420.

USGS (U.S. Geological Survey) 1998. *Probabilistic Seismic Hazard Analyses for Fault Displacement and Vibratory Ground Motion at Yucca Mountain, Nevada, Final Report* (3 volumes). Wong, I.G. and Stepp, J.C., Report Coordinators. Milestone Report SP32IM3. Oakland, California: CRWMS M&O. MOL.19980619.0640.

Vaniman, D.T., and Chipera, S.J. 1996. "Paleotransport of Lanthanides and Strontium Recorded in Calcite Compositions from Tuffs at Yucca Mountain, Nevada." *Geochimica et Cosmochimica Acta, 60,* 4417–4433. Oxford, New York: Pergamon Press. 231351.

Viani, B.E. and Bruton, C.J. 1996. *Assessing the Role of Cation Exchange in Controlling Groundwater Chemistry During Fluid Mixing in Fractured Granite at Aspo, Sweden.* UCRL-JC-121527. Livermore, California: Lawrence Livermore National Laboratory. 236539.

Wang, J.S.Y.; Trautz, R.C.; Cook, P.J.; Finsterle, S.; James, A.L.; Birkholzer, J.; Ahlers, C.F. 1998. *Testing and Modeling of Seepage Into Drift: Input of Exploratory Study Facility Seepage Test Results to Unsaturated Zone Models.* Milestone Report SP33PLM4. Berkeley, California: Lawrence Livermore National Laboratory. MOL.19980508.0004.

Whelan, J.F.; Vaniman, D.T.; Stuckless, J.S.; and Moscati, R.J. 1994. "Paleoclimatic and Paleohydrologic Records from Secondary Calcite: Yucca Mountain, Nevada." *High-Level Radioactive Waste Management: Proceedings of the Fifth Annual International Conference, Las Vegas, Nevada, May 22-26, 1994,* 2738–2745. La Grange Park, Illinois: American Nuclear Society. 222138.

Whitney, J.W. 1996. *Seismotectonic Framework and Characterization of Faulting at Yucca Mountain, Nevada.* Milestone 3GSH100M. Las Vegas, Nevada: USGS. MOL.19970129.0041.

Wilder, D.G. 1987. *Influence of Stress-Induced Deformations on Observed Water Flow in Fractures at the Climax Granitic Stock.* UCRL-95539, Rev. 01. Livermore, California: Lawrence Livermore National Laboratory. NNA.19880425.0044.

Wilder, D.G. 1997. *Near-Field and Altered-Zone Environment Report, Volume 1: Technical Bases for EBS Design.* UCRL-LR-107476, Vol. 1, Rev. 01. Livermore, California: Lawrence Livermore National Laboratory. MOL.19980107.0365.

Williams, D.F.; Thunell, R.C.; Tappa, E.; Rio, D.; and Raffi, I. 1988. "Chronology of the Pleistocene

Oxygen Isotope Record: 0-1.88 m.y. B.P." *Paleogeography, Paleoclimatology, and Paleoecology, 64*, 221–240. Amsterdam Netherlands: Elsevier Science Publishers B.V. 236879.

Wilson, M.L.; Gauthier, J.H.; Barnard, R.W.; Barr, G.E.; Dockery, H.A.; Dunn, E.; Eaton, R.R.; Guerin, D.C.; Lu, N.; Martinez, M.J.; Nilson, R.; Rautman, C.A.; Robey, T.H.; Ross, B.; Ryder, E.E.; Schenker, A.R.; Shannon, S.A.; Skinner, L.H.; Halsey, W.G.; Gansemer, J.D.; Lewis, L.C.; Lamont, A.D.; Triay, I.R.; Meijer, A.; and Morris, D.E. 1994. *Total-System Performance Assessment for Yucca Mountain–SNL Second Iteration (TSPA-1993)*. SAND93-2675. UC-814. Albuquerque, New Mexico: Sandia National Laboratories. NNA.19940112.0123.

Winograd, I.J.; Coplen, T.B.; Landwehr, J.M.; Riggs, A.C.; Ludwig, K.R.; Szabo, B.J.; Kolesar, P.T.; and Revesz, K.M. 1992. "Continuous 500,000-Year Climate Record from Vein Calcite in Devils Hole, Nevada." *Science, 258*, 255–260. Washington, D.C.: American Association for the Advancement of Science. 237563.

Winograd, I.J.; Landwehr, J.M.; Ludwig, K.R.; Coplen, T.B.; and Riggs, A.C. 1997. "Duration and Structure of the Past Four Interglaciations." *Quaternary Research, 48*, 141–154. New York, New York: Academic Press. 236777.

Winograd, I.J. and Thordarson, W. 1975. *Hydrogeologic and Hydrochemical Framework, South-Central Great Basin, Nevada-California, with Special Reference to the Nevada Test Site*. Professional Paper 712-C. Denver, Colorado: USGS. NNA.19870406.0201.

Wolery, T.J. and Daveler, S.A. 1992. *EQ6, A Computer Program for Reaction Path Modeling of Aqueous Geochemical Systems: Theoretical Manual, User's Guide, and Related Documentation (Version 7.0)*. UCRL-MA-110662, Part 4. Livermore, California: Lawrence Livermore National Laboratory. 205002.

Wolery, T.J.; Jackson, K.J.; Bourcier, W.L.; Bruton, C.J.; Viani, B.E.; Knauss, K.G.; and Delany, J.M. 1990. "The EQ3/6 Software Package for Geochemical Modeling: Current Status: American Chemical Society Symposium Series 416." *Chemical Modeling in Aqueous Systems II*, 104–116. Melchior, D.C. and Bassett, R.L., eds. Easton, Pennsylvania: American Chemical Society. 225589.

Yang, I. C.; Rattray, G.W.; and Yu, P. 1996. *Interpretation of Chemical and Isotopic Data From Boreholes in the Unsaturated Zone at Yucca Mountain, Nevada*. Water-Resources Investigations Report USGS-WRIR-96-4058. Denver, Colorado: USGS. MOL.19970715.0408.

Yang, I.C.; Yu, P.; Rattray, G.W.; and Thorstenson, D.C., 1997. *Hydrochemical Investigations and Geochemical Modeling in Characterizing the Unsaturated Zone at Yucca Mountain, Nevada.* Draft. Milestone Report 3GUH607M, Water-Resources Investigations Report. Denver, Colorado: USGS. MOL.19970415.0393.

Zyvoloski, G.A.; Robinson, B.A.; Birdsell, K.H.; Gable, C.W.; Czarnecki, J.; Bower, K.M.; and Faunt, C. 1997. *Saturated Zone Radionuclide Transport Model*. Milestone Report SP25CM3A. Los Alamos, New Mexico: Los Alamos National Laboratory. MOL.19980127.0089.

## 3.2 STANDARDS AND REGULATIONS

**Unless otherwise dated, the *Codes of Federal Regulations* cited in this document were revised as of January 1, 1998.**

10 CFR (*Code of Federal Regulations*) 20. Energy: Standards for Protection Against Radiation. 238505.

10 CFR 60. Energy: Disposal of High-Level Radioactive Wastes in Geologic Repositories. 238445.

10 CFR 960. Energy: Nuclear Waste Policy Act of 1982; General Guidelines for the Recommendation of Sites for the Nuclear Waste Repositories. 238500.

10 CFR 1021. Energy: National Environmental Policy Act Implementing Procedures. 238426.

46 FR (*Federal Register*) 26677 (1981). Program of Research and Development for Management and Disposal of Commercially Generated Radioactive Wastes; Record of Decision. 238428.

61 FR 66158 (1996). 10 CFR 960. Energy: General Guidelines for the Recommendation of Sites for Nuclear Waste Repositories; Notice of Proposed Rulemaking. 238558.

Atomic Energy Act of 1954 as amended. Public Law 85-256, 68 Stat. 921; 42 U.S.C. 2011 et seq. 219223.

Energy and Water Development Appropriations Act, 1997. Public Law 104-206, 110 Stat. 2984. 238115.

Energy Policy Act of 1992. Public Law 102-486, 106 Stat. 2276; 42 U.S.C. 10141 et seq. 233191.

Energy Reorganization Act of 1974. Public Law 93-438, 88 Stat. 1233; 42 U.S.C. 5801 et seq. 233293.

National Environmental Policy Act of 1969. Public Law 91-190, 83 Stat. 852; 42 U.S.C. § 4321 et seq. 218478.

Nuclear Waste Policy Act of 1982. Public Law 97-425. 96 Stat. 2201; 42 U.S.C. 10101 et seq. 216801.

Nuclear Waste Policy Amendments Act of 1987. Public Law 100-203, 101 Stat. 1330. 223717

Resource Conservation and Recovery Act of 1976. Public Law 94-580. 238124.

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# APPENDIX A

# GLOSSARY

## APPENDIX A

## GLOSSARY

Many of the definitions in this glossary are Yucca Mountain Project specific.

| | |
|---|---|
| Algorithm | (1) The set of well-defined rules that govern the solution of a problem in a finite number of steps. (2) A mathematical formulation of a model of a physical process. |
| Alluvium | Sedimentary material (clay, mud, sand, silt, gravel) deposited by flowing water or by wind. |
| Anisotropic | The condition in which physical properties vary when measured in different directions or along different axes. |
| Aquitard | A leaky confining bed that transmits water at a very slow rate to or from an adjacent aquifer. |
| Argillite | A rock derived from siltstone, claystone, or shale that has undergone a higher degree of hardening than those from which it has been formed. |
| Assemblage | A general collection of objects or items. |
| Attenuation | A weakening or reduction in amplitude. |
| Backfill | (1) The general fill that is placed in the excavated areas of the underground facility. Backfill for the repository will be tuff. (2) The material or process used to refill an excavation. |
| Basalt | A dark, fine-grained igneous rock originating from a lava flow or minor intrusion, composed mainly of plagioclase clinopyroxene, and sometimes olivine, and often displaying a columnar structure. |
| Benchmark | A standard of measurement or evaluation. |
| Caldera | An enlarged volcanic crater formed by explosion or collapse of the original crater. |
| Cation | An ion that bears a positive charge. |
| Cenozoic Era | The most recent geologic era, extending from the beginning of the Tertiary Period to the present. |
| Characterization | See "Site Characterization." |
| Clastic | Describing a rock or sediment composed mainly of broken fragments of preexisting minerals or rocks that have been transported from their places of origin. |
| Climate | Long-term weather conditions, including temperature, wind direction, precipitation, and other factors, that prevail in a region. |

| | |
|---|---|
| Colluvium | Any loose, heterogeneous sediment deposited by rainwash, sheetwash, or slow continuous downslope creep, usually at the base of a cliff or slope. |
| Complexation | The process of two or more chemical species, in solution, combining to form a third. |
| Criticality | The condition in which nuclear fuel sustains a chain reaction. It occurs when the number of neutrons present in one generation cycle equals the number generated in the previous cycle. For the TSPA-VA, it is a condition that would require the original waste form, which is part of the waste package, to be exposed to degradation followed by conditions that would allow concentration of sufficient nuclear fuel, the presence of neutron moderators, the absence of neutron absorbers, and favorable geometry. |
| Darcies | A unit of permeability defined as the passage of 1 cc of fluid, having 1 centipoise viscosity, flowing in 1 second under a pressure of 1 atmosphere, through a porous medium having a length of 1 cm and a cross-sectional area of 1 $cm^2$ (1 darcy equals $1x10^{-12}$ $m^2$). |
| Deformation | Any change in the shape and size of a body. |
| Diffusivity | A measure of the rate of heat diffusion. It varies with the nature of the involved atoms, the structure, and changes in temperature. |
| DOE Siting Guidelines | Define general siting guidelines provided by the U.S. Department of Energy in 10 CFR 960. Guidelines include several criteria considered "favorable" and "unfavorable" against which a site could be evaluated. |
| Drift | From mining terminology, a horizontal underground passage. The nearly horizontal underground passageways from the shaft(s) to the alcoves and rooms. Includes excavations for emplacement (emplacement drifts) and access (access mains). |
| Drip Shield | A sheet of impermeable material placed above the waste package to prevent seepage water from directly contacting the waste packages. |
| Energy Policy Act of 1992, Public Law 102-486 | Comprehensive energy legislation enacted in 1992. Section 801 of the Act directs the U.S. Environmental Protection Agency (EPA) to contract with the National Academy of Sciences to provide "findings and recommendations on reasonable standards...that would govern the long-term performance of a repository at the Yucca Mountain site." The EPA administrator is to promulgate public health and safety standards after the receipt of the findings and recommendations of the National Academy of Sciences, and these shall be the only standards applicable to the Yucca Mountain site. |

| | |
|---|---|
| Environmental Impact Statement (EIS) | A detailed written statement to support a decision to proceed with major federal actions affecting the quality of the human environment. This is required by the National Environmental Policy Act. Environmental impact statement (EIS) means the document required by Section 102(2)(C) of the National Environmental Policy Act of 1969. Sections 114(a) and 114(f) of the Nuclear Waste Policy Act of 1982 include certain limitations on the National Environmental Policy Act requirements as they apply to the preparation of an EIS for the development of a repository at a characterized site. |
| Epidemiological | Pertaining to the branch of medicine that studies epidemics and diseases. |
| Evapotranspiration | The combined processes of evaporation and plant transpiration that remove water from the soil and return it to the air. |
| Fissionable | Having heavy radioactive atomic nuclei that can be divided into smaller parts, which are referred to as fission products. |
| Geothermal Gradient | The increase in the earth's temperature with increasing depth from the surface due to the earth's internal heat. Measurements are generally expressed in degrees C per unit depth. |
| Groundwater | As used in the TSPA-VA, water contained in pores or fractures in either the unsaturated or saturated zones below ground level. |
| Hydraulic Conductivity | A number that describes the rate at which water can move through a permeable medium. The hydraulic conductivity depends on the size and arrangement of water-transmitting openings such as pores and fractures, the dynamic characteristics of the water such as density and viscosity, and the strength of the gravitational field. |
| Imbibition | The absorption of a fluid, usually water, by porous rock (or other porous material) under the force of capillary attraction and without pressure. |
| Isotope | One of two or more atomic nuclei with the same number of protons (i.e., the same atomic number) but with a different number of neutrons (i.e., a different atomic weight). For example, uranium-235 and uranium-238 are both isotopes of uranium. |
| Iterative | Refers to conditions or results that are repeated in an analysis. For TSPA-VA, it is the processes in which analysts rerun calculations or refine models as new data are gathered or new insights occur. |
| Lanthanide Elements | The set of chemically related rare-earth elements with atomic numbers from 57 to 71. |
| License Application | An application to the Nuclear Regulatory Commission for a license, such as one to construct a repository. |

| | |
|---|---|
| Lithology | The physical characteristics of a rock as determined by examination under megascopic or low power magnification conditions. It is also the microscopic study and description of rocks. |
| Lithostratigraphic | Rock or earth material defined by a set of similar characteristics that usually relate to origin such as rock from volcanoes, rivers, or oceans. |
| Mesozoic Era | The geologic era extending from the end of the Paleozoic Era to the beginning of the Cenozoic Era, dating from approximately 230 million to 65 million years ago. |
| Metastability | A solid, liquid, or gas that is not thermodynamically stable, but that persists unless acted upon by a change in the system, such as variation in pressure, temperature, or fluid composition. |
| Meteorology | Short-term weather conditions lasting from a few minutes to a few years. |
| Metric Ton of Heavy Metal (MTHM) | A metric ton is a unit of mass equal to 1,000 kg (2,205 lb). Heavy metals are those with atomic weights greater than 230. Examples include thorium, uranium, plutonium, and neptunium. When used in the Civilian Radioactive Waste Management Program, the term usually pertains to heavy metals in spent nuclear fuel. |
| Miocene | The fourth of the five geologic epochs of the Tertiary Period, extending from the end of the Oligocene Epoch to the beginning of the Pliocene Epoch. |
| Natural Analogs | Natural geologic systems that parallel situations that can develop in manmade systems, in which the formation and transport of minerals over hundreds of thousands and millions of years can be studied directly. An example of a natural analog is the natural reactor studied at the Oklo uranium deposit in Gabon, Africa, which can be used as a source of analog data for conceptual models of criticality. |
| Near-Field Environment | The condition of the area near the repository. This condition may change because of heat, water influx, and chemical changes in the rock itself. |
| Nuclear Waste Policy Act (42 USC 10101, et seq.) | The federal statute enacted in 1982 that established the Office of Civilian Radioactive Waste Management and defined its mission to develop a federal system for the management and geologic disposal of commercial spent nuclear fuel and other high-level radioactive wastes, as appropriate. The Act also specified other federal responsibilities for nuclear waste management, established the Nuclear Waste fund to cover the cost of geologic disposal, authorized interim storage under certain circumstances, and defined interactions between federal agencies and the states, local governments, and Indian tribes. The Act was substantially amended in 1987 and 1992. |
| Oligocene | The third of five geologic epochs of the Tertiary Period, extending from the end of the Eocene Epoch to the beginning of the Miocene Epoch. |

| | |
|---|---|
| Order of Magnitude | Approximately a factor of ten. |
| Oxidation | (1) A chemical reaction, such as the rusting of iron, that increases the oxygen content of a substance. (2) A reaction in which the valence of an element or compound is increased as a result of losing electrons. |
| Paleozoic Era | A geologic era extending from the end of the Precambrian to the beginning of the Mesozoic, dating from about 600 million to 230 million years ago. |
| Perched | (Same as perched groundwater). Unconfined groundwater separated from an underlying body of groundwater by an unsaturated zone. |
| Performance Confirmation | The program of tests, experiments, and analysis conducted to evaluate the accuracy and adequacy of the information used to determine, with reasonable assurance, that the performance objectives for the period after permanent closure will be met. |
| Plate Tectonics | A branch of geology that deals with the theory that the earth's surface is composed of a small number of large, semirigid sections that float across the underlying mantle, with seismic activity and volcanism occurring primarily at the junction of these sections. |
| Pleistocene | The first of the two geologic epochs of the Quaternary Period extending from the end of the Pliocene Epoch to the beginning of the Holocene, and the rocks formed during that time. |
| Pliocene | The last of the five geologic epochs of the Tertiary Period extending from the end of the Miocene to the beginning of the Pleistocene, and the rocks formed during that time. |
| Plutonic | Pertaining to the formation of igneous rock bodies beneath the earth's surface, as opposed to volcanic, which refers to igneous activity at the surface. |
| Postclosure Period | Refers to the period of time after the closure of a monitored geologic repository. |
| Potentiometric Surface | An imaginary surface (including the water table) defined by the level to which water will rise in a well under its full pressure head, and representing the total static level of groundwater. |
| Precambrian Era | The era that includes all geologic time from the formation of the earth to the beginning of the Paleozoic Era (from about 4.5 billion to 600 million years ago). |
| Preclosure Period | Refers to the period of time before and during the closure of a monitored geologic repository. |
| Pyroclastic | Of or relating to individual particles or fragments of clastic rock material of any size that is formed by volcanic explosion or ejected from a volcanic vent. |

| | |
|---|---|
| Quaternary | The second period of the Cenozoic Era, beginning about 2 million years ago at the end of the Tertiary Period and extending to the present. |
| Radiogenic | An attribute of a nuclide that has been derived from a radioactive parent nuclide. |
| Reducing Conditions | An environment where electrons from one atom are easily attracted to another atom. |
| Rockbolt | (1) A bar, usually constructed of steel, that is anchored into predrilled holes in rock as a support or reinforcement device. (2) The method of ground support using such devices to support walls and ceilings in underground excavations. |
| Seismic | Pertaining to, characteristic of, or produced by earthquakes or earth vibration. |
| Site Characterization | Activities, whether in the laboratory or in the field, undertaken to establish the geologic conditions and the ranges of the parameters of a candidate site relevant to the location of a repository. These activities include borings, surface excavations, excavations of exploratory shafts, limited subsurface lateral excavations and borings, and in situ testing needed to evaluate the suitability of a candidate site for the location of a repository, but do not include preliminary borings and geophysical testing needed to assess whether site characterization should be undertaken. |
| Sorb | To undergo a process of sorption. |
| Sorption | The binding, on a microscopic scale, of one substance to another, and includes both adsorption and absorption. In this document, the word is especially used for the sorption of dissolved radionuclides onto aquifer solids or waste package materials by means of close-range chemical or physical forces. |
| Sorption Coefficient ($K_d$) | Coefficient for a term for the various processes by which one substance binds to another. |
| Steel Sets | Steel tunnel supports used in main entries of mines and shafts. The sections are I-beams for caps and H-beams for posts or wall plates, the H-section giving equal stiffness in two directions at right angles to each other. |
| Stratigraphy | The branch of geology that deals with the definition and interpretation of rock strata, the conditions of their formation, character, arrangement, sequence, age, distribution, and especially their correlation by the use of fossils and other means of identification. |

| | |
|---|---|
| Systems Engineering | (1) The application of scientific and engineering principles to control a complex total-system development effort to achieve the best balance of all system elements. (2) A process that transforms and integrates operational needs and requirements into a description of system requirements to maintain the overall system effectiveness. |
| Tectonic | Pertaining to geologic forms or effects created by deformation of the earth's crust. |
| Tertiary | The first of two geologic periods of the Cenozoic Era extending from the end of the Mesozoic Era to the beginning of the Quarternary Period, covering a time span from about 63 million to about 2 million years ago. |
| Thermal Loading | (1) The application of heat to a system, usually measured in terms of watt density. The thermal loading for a repository is the watts per acre produced by the radioactive waste in the active disposal area. (2) The spatial density at which waste packages are emplaced within the repository as characterized by the areal power density and the areal mass loading. |
| Transmissivity | The rate at which water is transmitted through a unit width of the aquifer under a unit hydraulic gradient. It equals the hydraulic conductivity multiplied by the thickness of the aquifer. |
| Tritium | A radioactive isotope of hydrogen that can be taken into the body easily, because it is chemically identical to natural hydrogen. Tritium decays by beta emission with a half-life of about 12.5 years. |
| Tuff | Igneous rock formed from compacted volcanic fragments from pyroclastic (explosively ejected) flows with particles generally smaller than 4 mm in diameter. The most abundant type of rock at the Yucca Mountain site. |
| Unsaturated Zone | The zone of soil or rock between the land surface and the water table. |
| Vitrophyre | An igneous rock containing large crystals in a pronounced glassy groundmass. |
| Waste Package | The waste form and any shielding, packing, and other absorbent materials immediately surrounding the waste. |
| Water Table | The upper surface of a zone of saturation above which the majority of pore spaces and fractures are less than 100 percent saturated with water most of the time (unsaturated zone) and below which the opposite is true (saturated zone). |
| Zeolitic | Of or pertaining to a large group of hydrous aluminosilicate minerals that act as molecular "sieves" because they can adsorb molecules with which they interact. At Yucca Mountain, they are secondary alteration products in tuff rocks when the rocks are exposed to groundwater and could act to retard the migration of radionuclides by their sieving action. |

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# APPENDIX B

# AS-BUILT GEOLOGY OF THE ECRB CROSS DRIFT

# APPENDIX B

# AS-BUILT GEOLOGY OF THE ECRB CROSS DRIFT

## B.1 INTRODUCTION

As of August 6, 1998, the Enhanced Characterization of the Repository Block (ECRB) cross drift had been excavated to approximately Station 12+60, about 500 m (1,640 ft) beyond the main drift. Geologic mapping at a scale of 1:125 has been completed to approximately 10+00, and rock mass classification has been completed to approximately Station 9+50.

## B.2 LITHOSTRATIGRAPHY

The lithology of the cross drift (up to 12+60) is mostly as anticipated. The cross drift begins in a pyroclastic flow unit, the Topopah Spring tuff, crystal-poor, upper lithophysal zone (Tptpul) (Figures B-1 and B-2). (For more information on detailed lithostratigraphic nomenclature, see CRWMS M&O 1998d, Section 3.5). The tunnel continues in the same unit to approximately Station 10+60; the unit had been predicted to extend to 11+35. The Tptpul is a densely welded, devitrified, moderately hard to hard, light gray, lithophysae-bearing, rhyolitic tuff. Lithophysae range from 10 to 40 percent by volume and range in size from millimeters to tens of centimeters (locally 1 m). Beyond Station 10+60, the tunnel was excavated through the Topopah Spring tuff, crystal-poor member, middle nonlithophysal zone (Tptpmn). The Tptpmn is a densely welded, devitrified, moderately hard to hard, light gray to grayish orange, nonlithophysal, rhyolitic tuff.

In addition to the lithostratigraphy of the cross drift discussed above, Figures B-1 and B-2 also show the thermal-mechanical stratigraphy. This stratigraphic system was developed to provide a systematic basis for characterizing the rock mass in the site area based on geoengineering properties. It is based on thermal and mechanical rock characteristics that are important to repository design.

## B.3 STRUCTURE

The cross drift is being geologically mapped by two different methods—full periphery mapping and detailed line surveys. The full periphery method comprises drawing the traces of geologic features longer than 1 m (3.28 ft) onto a base map which represents an unrolled view of the tunnel walls. Detailed line surveys involve measuring various parameters of geologic features longer than 1 m (3.28 ft), which intersect the center of the left wall of the tunnel.

Three small faults were predicted for interception by the cross drift between stations 0+00 and 12+00—a splay of the Drill Hole Wash fault at Station 1+30, the Ghost Dance fault at Station 4+80, and the Sundance fault between Stations 10+70 and 11+00 (Figure 2-8). The Drill Hole Wash fault was not observed in the cross drift. A fracture was encountered at Station 4+99, oriented 175/85 (strike/dip), which is correlated with the distal end of the Ghost Dance fault. The fracture has no discernible offset but does display 1–2 cm of clayey infilling. Some minor fallout occurred along the feature (less than 0.5 m, or 1.6 ft), but the feature had no significant effect on tunneling operations or ground support. No mineralization was observed along the feature.

At Station 11+35, the Sundance fault was encountered. The fault plane is oriented 147/82 (strike/dip) and has an approximately 1-m (3.3-ft) thick zone of intensely fractured wall rock on the hanging wall. The footwall is relatively unfractured. Rock on both sides of the fault is the Topopah Spring, middle non-lithophysal zone (Tptpmn).

Fractures from full-periphery mapping were combined with detailed line surveys in the cross drift from Station 0+00 to 7+00, a total of 333 features. Using only the detailed line survey fractures, there are 0.14 fractures per meter in the Tptpul between Station 0+00 and 7+00 in the cross drift). This compares with 0.7 fractures per meter observed in the Exploratory Studies Facility.

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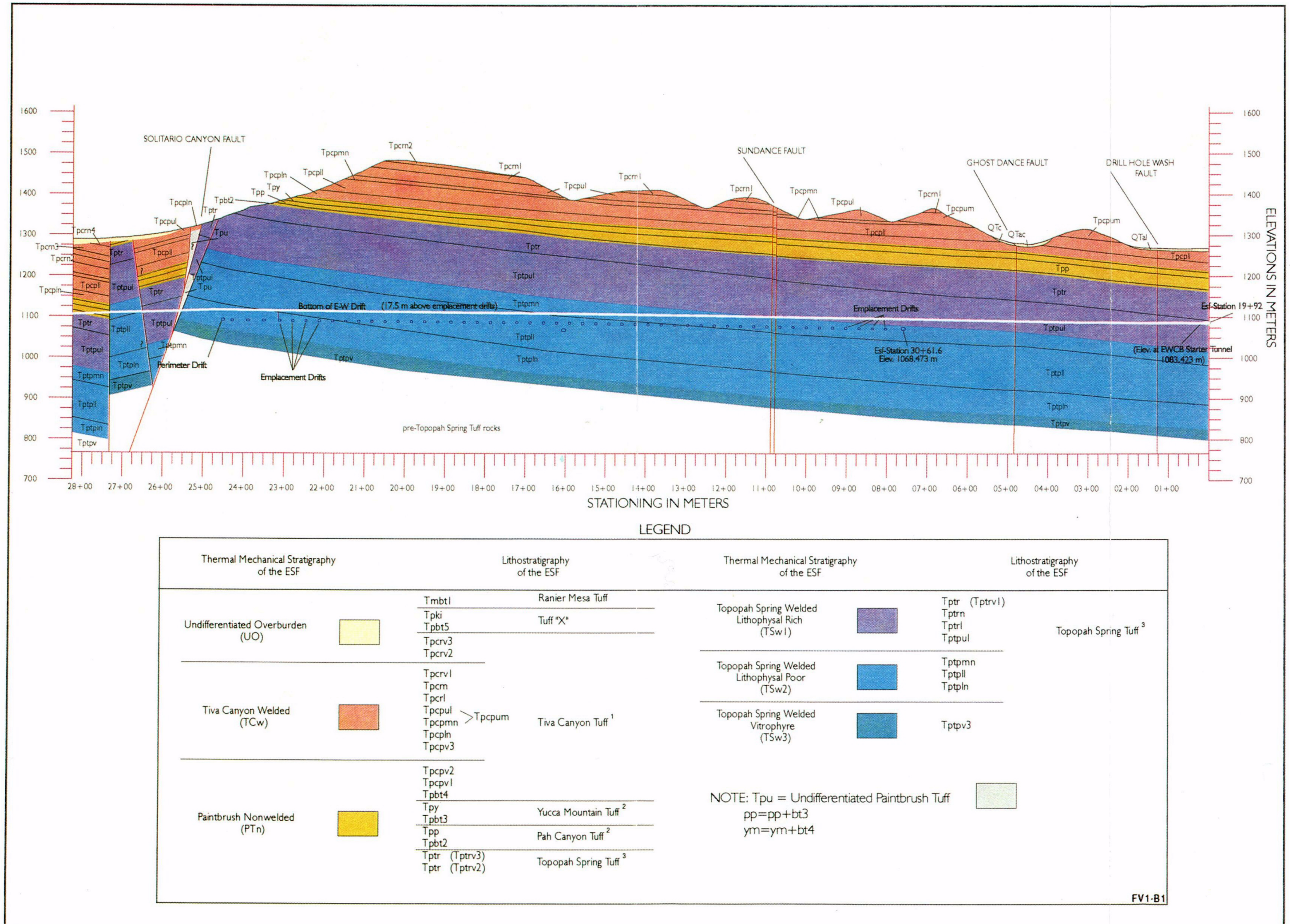


Figure B-1. Pre-Construction Geologic Cross Section of the ECRB Cross Drift

1. Corresponds to Tiva Canyon Tuff crystal-rich and crystal-poor members on Figure 2-9.
2. Corresponds to Pre-Tiva Canyon tuff bedded tuffs on Figure 2-9.
3. Corresponds to Topopah Spring Tuff crystal-rich and crystal-poor members on Figure 2-9.



C-8

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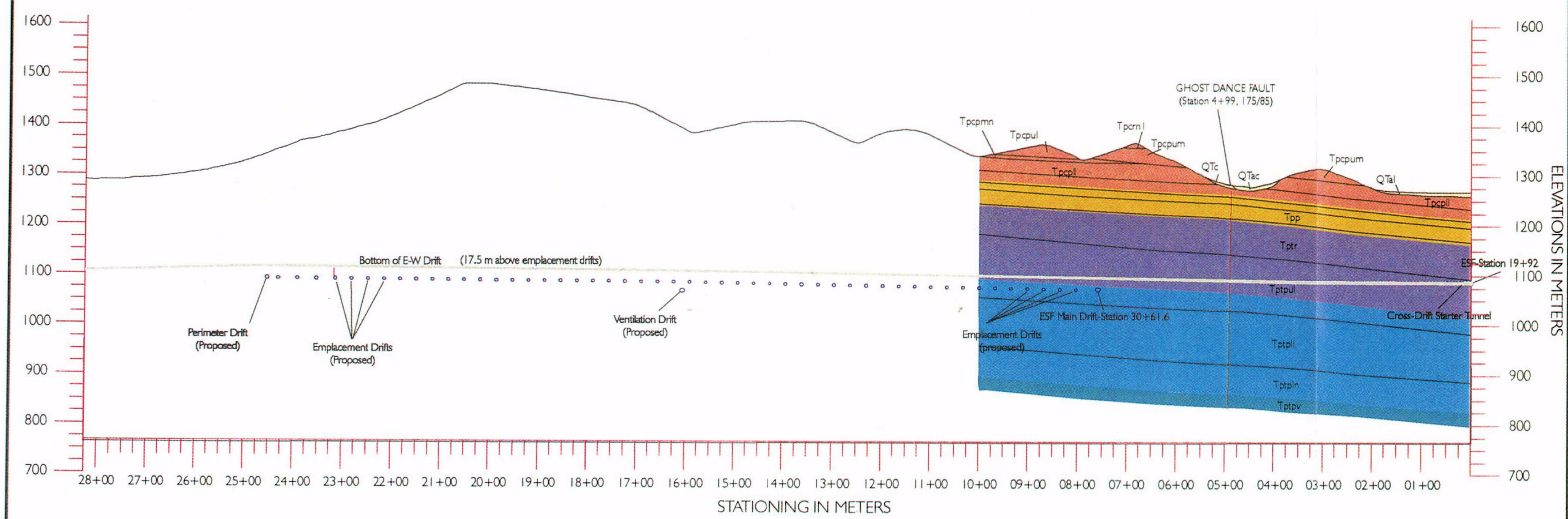


LEGEND

| Thermal Mechanical Stratigraphy of the ESF | | Lithostratigraphy of the ESF | |
|---|---|---|---|
| Undifferentiated Overburden (UO) | (pale yellow) | Tmbt1 | Ranier Mesa Tuff |
| | | Tpki<br>Tpbt5 | Tuff "X" |
| | | Tpcrv3<br>Tpcrv2 | |
| Tiva Canyon Welded (TCw) | (red) | Tpcrv1<br>Tpcrn<br>Tpcrl<br>Tpcpul<br>Tpcpmn > Tpcpum<br>Tpcpln<br>Tpcpv3 | Tiva Canyon Tuff [1] |
| Paintbrush Nonwelded (PTn) | (yellow) | Tpcpv2<br>Tpcpv1<br>Tpbt4 | |
| | | Tpy<br>Tpbt3 | Yucca Mountain Tuff [2] |
| | | Tpp<br>Tpbt2 | Pah Canyon Tuff [2] |
| | | Tptr (Tptrv3)<br>Tptr (Tptrv2) | Topopah Spring Tuff [3] |

| Thermal Mechanical Stratigraphy of the ESF | | Lithostratigraphy of the ESF | |
|---|---|---|---|
| Topopah Spring Welded Lithophysal Rich (TSw1) | (purple) | Tptr (Tptrv1)<br>Tptm<br>Tptrl<br>Tptpul | Topopah Spring Tuff [3] |
| Topopah Spring Welded Lithophysal Poor (TSw2) | (blue) | Tptpmn<br>Tptpll<br>Tptpln | |
| Topopah Spring Welded Vitrophyre (TSw3) | (dark blue) | Tptpv3 | |

NOTE: Tpu = Undifferentiated Paintbrush Tuff
pp=pp+bt3
ym=ym+bt4

FV1-B2

1. Corresponds to Tiva Canyon Tuff crystal-rich and crystal-poor members on Figure 2-9.
2. Corresponds to Pre-Tiva Canyon tuff bedded tuffs on Figure 2-9.
3. Corresponds to Topopah Spring Tuff crystal-rich and crystal-poor members on Figure 2-9.

Figure B-2. As-Built Geologic Cross Section of the ECRB Cross Drift



C-09

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Three of the predominant fracture sets from mapping the Tptpul in the Exploratory Studies Facility had peak orientations that are comparable to peak orientations observed in the cross drift:

| Predicted from Exploratory Studies Facility | Observed in Cross Drift |
|---|---|
| 182/81 | 185/84 |
| 219/83 | 209/85 |
| 114/87 | 121/87 |

In summary, the rock encountered in the cross drift is as expected. Testing continues in Niches 1 and 2, with drilling proceeding in Niche 4. The cross drift is expected to be completed by the end of September 1998, when the drift crosses the Solitario Canyon fault.

## B.4 COMPARISON OF ROCK QUALITY FOR Tptpul

Scientists have collected data quantifying the overall quality of the rock mass in the cross drift. Data was collected and processed through three different systems—rock mass qualification index, rock mass rating, and rock quality description. The parameters within the cross drift were measured to Station 6+00 at 5-m (16.4-ft) intervals. A comparison of predicted and actual values is presented in Table B-1.

Table B-1. Rock Mass Quality Values

| Tptpul Rock Mass Quality | | Predicted | Actual |
|---|---|---|---|
| **Q** | Average Value | 5.1 | 19 |
| | Minimum | 0.2 | 0.3 |
| | Maximum | 54 | 52 |
| **RMR** | Average Value | 58 | 62 |
| | Minimum | 49 | 43 |
| | Maximum | 73 | 80 |
| **RQD** | Average Value | Not predicted | 41 |
| | Minimum | Not predicted | 1 |
| | Maximum | Not predicted | 94 |

Q = Rock mass qualification index
RMR = Rock mass rating
RQD = Rock quality description

## B.5 ACTUAL VERSUS PREDICTED FEATURE LOCATIONS AS OF JULY 24, 1998

Table B-2 shows a summary of expected features and locations and where the features were actually encountered in the cross drift.

Table B-2. Predicted Versus Actual Feature Locations

| Feature | Predicted Station | As-Built Station | Comments |
|---|---|---|---|
| Upper lithophysal zone of the Topopah Spring tuff | 0+00 to 11+40 | 0+00 to 11+60 | Tunnel excavation intercepted the base of the zone earlier than predicted |
| Middle nonlithophysal zone of the Topopah Spring tuff | 11+40 to 16+70 | 10+60 to ? | Tunnel progress has not yet intercepted the base of the zone |
| Drill Hole Wash fault | 1+30 | Not encountered | |
| Ghost Dance fault | 4+80 | 4+99 | No offset visible in tunnel |
| Sundance fault | 10+70 to 11+00 | 11+35 | Offset not determined as yet |

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# APPENDIX C

# BUSTED BUTTE UNSATURATED ZONE TRANSPORT FIELD TEST

# APPENDIX C

# BUSTED BUTTE UNSATURATED ZONE TRANSPORT FIELD TEST

## C.1 BACKGROUND

Evaluations of the total system performance of a geologic repository at Yucca Mountain must examine cases in which some or all of the engineered barriers do not perform as designed for 10,000 years. Predicting possible radionuclide transport from the potential repository through the unsaturated zone to the water table and to the accessible environment is essential to these evaluations. DOE is evaluating the hydrologic and transport properties of the Calico Hills nonwelded tuff, the geologic unit below the repository horizon, to provide input to numerical models used to evaluate the transport of radionuclides through the unsaturated zone.

The unsaturated zone transport field test at Busted Butte, located approximately 5 km (3 miles) south of the potential repository at Yucca Mountain, is specifically designed to demonstrate the applicability of laboratory-scale transport data to field-scale transport processes. It will also provide information on radionuclide transport in the unsaturated zone that is presently unavailable but explicitly required by 10 CFR 60 for licensing.

The objective of the unsaturated zone transport field tests is to validate key assumptions and inputs to the large-scale, unsaturated zone transport model and to probabilistic unsaturated zone transport calculations. A major benefit of siting the unsaturated zone test at Busted Butte is that it is not an analog of the Calico Hills formation; it is an actual exposure of the formation to the south of the proposed repository location. Therefore, the findings are expected to be directly applicable to repository performance issues. A second major benefit is that tests at Busted Butte can be fielded and analyzed in time to produce results for TSPA for the LA.

The principal assumptions and inputs being tested at Busted Butte include, but are not restricted to, the following:

- Migration of colloids in fractured and unfractured Calico Hills rocks under unsaturated conditions
- Field validity of laboratory sorption and transport measurements of the key radionuclides (plutonium, technetium, neptunium, iodine, and americium)
- Effects of heterogeneities in Calico Hills rocks (e.g., fractures and permeability contrasts between welded and nonwelded tuffs) on solute migration under unsaturated and partially saturated conditions, using a stochastic modeling approach
- Validity of the three-dimensional equivalent continuum/dual permeability/discrete fault representations of the site-scale, unsaturated zone, flow and transport model
- Scaling of laboratory, field-flow, and transport results to the Yucca Mountain site scale
- Calibration, from the field tracer tests, of the radionuclide transport model for surface complexation and ion exchange

## C.2 DESCRIPTION OF UNSATURATED ZONE TEST AT BUSTED BUTTE

The unsaturated zone field transport test at Busted Butte has been designed to proceed in three phases. Each phase includes reactive and nonreactive unsaturated tuff transport tests. Data from phases I and II will feed detailed flow and transport process models for LA as well as abstractions of these models for performance assessments. Phase III tests are proposed as part of the performance confirmation program following the LA. A description of the first two phases follows.

Phase I includes 5-month-long reactive and nonreactive tracer tests in 2-m (6.5-ft) boreholes with overcoring at the end of the tests to determine tracer mobility in three dimensions. In Phase Ia, there are four, single point injection boreholes in the nonfractured upper Calico Hills. The rates of injection vary between boreholes. In Phase Ib, there are two, single-point injection boreholes in the fractured hydrologic Calico Hills (VI unit of the nonwelded unit below the basal vitrophere of the Topopah Springs) that have inverted membrane, tracer collection boreholes approximately 30 cm (12 in.) directly below them. A schematic of the Busted Butte test bock is shown in Figure C-1.

Phase II is the main testing phase of the Busted Butte unsaturated flow and transport test. This phase involves 13–18 month reactive and nonreactive tracer tests in a 10 × 10 × 6-m (33 × 33 × 20-ft) underground test block in the hydrologic Calico Hills (V1 and V2 units) and upper 2 m (6.5 ft) of the Calico Hills. The Phase II test design consists of 10 multipoint injection boreholes emanating from the test Alcove and 12 inverted membrane, tracer collection boreholes in the main adit (see test plan figure). This test will investigate the heterogeneities being tested in the Phase Ia and Ib tracer tests on a larger scale.

The reactive and nonreactive tracers used in the Phase I and II tests were chosen to closely mimic the key radionuclides used in the transport models that have the greatest effect in dose for performance assessment calculation. The tracers being used in Phase I tests are potassium iodide, lithium bromide, sodium fluorescein, various polyfluorinated benzoic acids, and two sizes of fluorescent polystyrene latex microspheres.

The Phase II tests require unique identification of each injection borehole. To do this, the conservative tracers potassium iodide, pyridone (a fluorescent trace), and five different polyfluorinated benzoic acids are being used. Together, these tracers from a set of seven different and distinguishable conservative solutes that will be used to "tag" specific injection boreholes. Estimates of transverse dispersivity will be obtained from observing how injected tracer solutions from different boreholes spread out and mix. Additional fluorescent tracers being used in Phase II are two sizes of polystyrene latex microspheres (an analog for colloids), sodium fluorescein, and rhodamine WT (water tracer), which may behave either as conservative or very weakly sorbed solutes in this system.

The reactive tracers used in Phase II tests and their radioactive analogs are:

- Nickel, cobalt, manganese (neptunium analogs)
- Samarium, molybdenum, and neutral polystyrene microspheres (soluble and colloidal plutonium analogs)
- Cerium, europium, neodymium (americium analogs)
- Rhenium, molybdenum, selenium (technetium analogs)

## C.3 RESULTS AND PREDICTIONS

### C.3.1 Field Test Results To Date

A. Injection of tracers into Phase Ia boreholes has been occurring since April 2, 1998. Two holes have injection rates of 1 mL (0.03 oz) per hour and two holes at 1 mL (0.03 oz) per hour. Total tracer solution injected into these holes through June 1998 is 34.1 L (9 gal). Phase Ia is a blind test, as there are no collection boreholes. Plans are to overcore these boreholes in September 1998 and examine flow and transport of the injected tracers through these rocks. Formal predictions of expected flow and transport results based on current rock, geologic, and hydrologic properties in the Yucca Mountain database will be made before overcoring of these holes.

B. Injection of tracers into Phase Ib boreholes has been occurring since May 2, 1998. One borehole has an injection rate of 1 mL (0.03 oz) per hour and the other is at 10 mL (0.34 oz) per hour. Total tracer solution injection through June 1998 is 10.6 L (2.8 gal). In the Phase Ib collection boreholes, only the 10 mL (0.34 oz) per

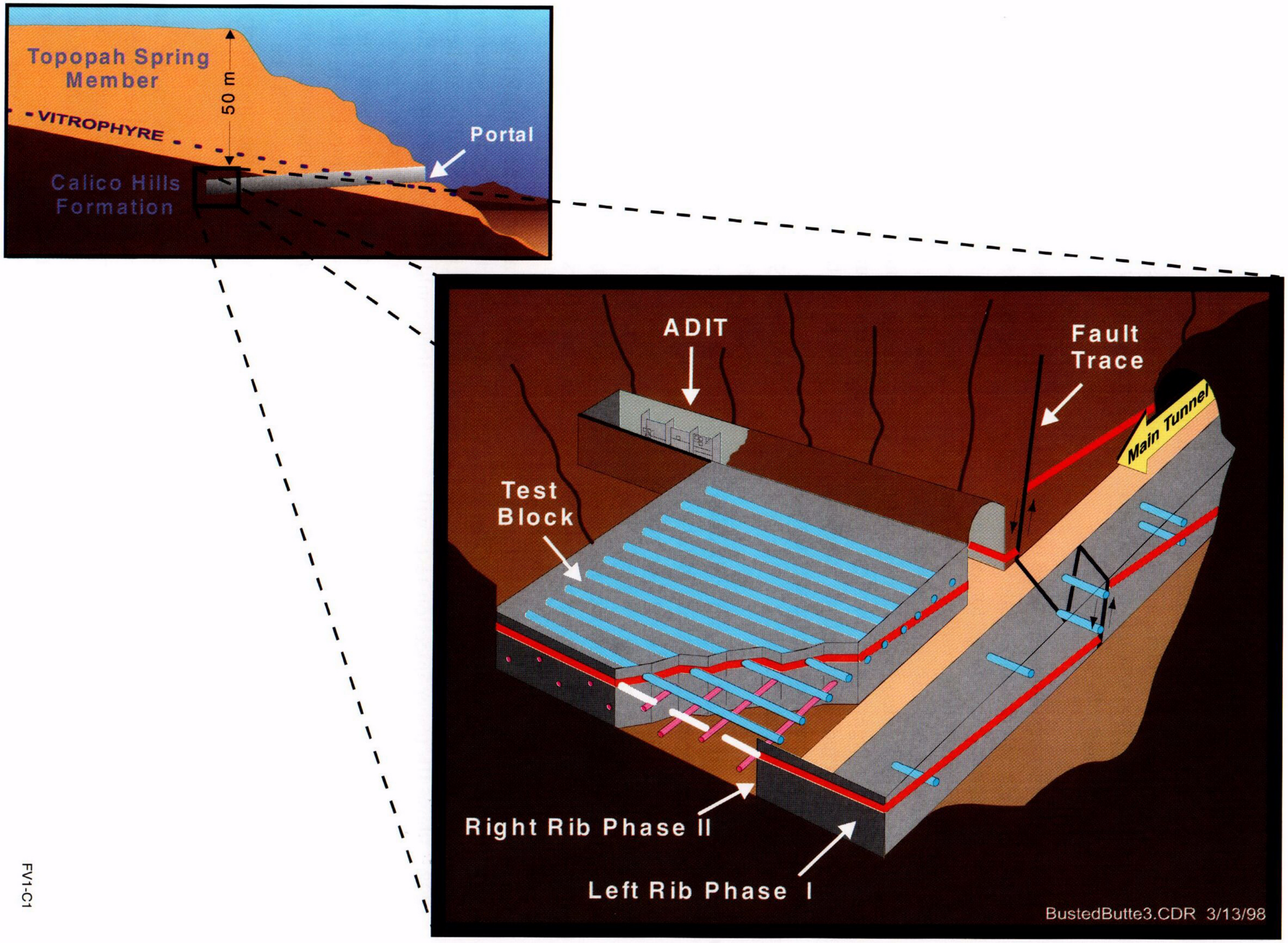


Figure C-1. Busted Butte Test Block

FV1-C1

C-10

hour injection test has showed tracer breakthrough. This breakthrough occurred about 30 days after injection. The tracer traveled about 1 cm (0.4 in.) per day at this injection rate. Current models would have predicted tracer breakthrough in hours to days based on existing fracture/matrix flow mechanisms in these models. The milliliter per hour injection test has not showed tracer breakthrough yet.

C. Baseline geophysics has been done on the Phase II test block including neutron logging, electrical resistivity, tomography, and ground penetrating radar. All the Phase II holes have also been air-permeability tested and video logged using plain and ultraviolet light. Geophysical tests will be conducted at specified intervals during testing to monitor the tracer front as it moves down into the block.

D. All the Phase II injection and collection systems have been fabricated, installed, and calibrated. The Phase II tests are being divided into three startup phases. The Phase IIa test consists of one injection hole, with 10 injectors injecting at a rate of 1 mL (0.03 oz) per hour. This injection rate most closely matches the natural infiltration rate at Yucca Mountain. The Phase IIa tracer injection test began July 23, 1998. Phase IIb tracer injection tests will consist of four injection holes, each with 10 injectors injecting at a rate of 10 mL (0.34 oz) per hour. Phase IIb tests will start about one week after Phase IIa. Phase IIc tracer injection tests will consist of three injection holes, each with 10 injectors injecting at a rate of 50 mL (1.7 oz) per hour. Phase IIc tests will start about one week after Phase IIb.

### C.3.2 Formal Predictions To Date

For the Phase II tests at Busted Butte, the first "blind" predictions of reactive and nonreactive tracer transport as well as hydrologic flow information have been developed using existing data from the Yucca Mountain hydrologic and geochemical databases and the current unsaturated zone flow and transport models. No new information from the Busted Butte site was used in these preliminary Phase II predictions, making them truly "blind." These predictions will be refined as data become available from the unsaturated zone transport test. A summary of the predictions follows:

A. Modeling results for fluorescein, a conservative tracer, indicate that tracer breakthrough is expected at several sampling locations within the first year of testing. For some sampling locations, tracer breakthrough is predicted for travel times of less than a month. Tracer breakthroughs could be even quicker than predicted if the equivalent continuum model assumption does not hold. Fracture flow through the Topopah Springs formation (Tptpv2) could result in faster travel times. The fracture parameters for the van Genuchten model are not known to a high degree of accuracy. Sensitivity analyses on these parameters will be performed to determine how sensitive travel times are to these fracture parameters.

   Another caveat in these modeling results is the effect of physical heterogeneities within each layer. Small-scale heterogeneities could result in preferential flow paths, which result in faster flow paths in some parts of the block and slower flow paths in other parts of the block. In the future, Monte Carlo simulations and more elegant stochastic techniques will be used to attempt to capture the uncertainty in the travel times.

B. More uncertainty exists in the predicted travel times of the reactive tracers than in the conservative tracer predictions. The strongly sorbing tracers manganese and cobalt (or nickel) are not expected to break through within the first year of testing. Even weakly sorbing lithium only reaches a few collection boreholes. Therefore, an additional year of operation may be required to achieve reactive tracer transport distances that reach more sampling points. At this stage, it is important to note that the model is extremely sensitive to the $K_d$s used for the tracers, and these $K_d$s are preliminary. (A $K_d$ for a dissolved solid is the distribution coefficient between the solution and the solid.) In addition, a linear $K_d$ model may not be sufficient to model sorption of these tracers due to chemical heterogeneities and nonlinear reactions. More rigorous reactive transport models will be used in the future to check the linear $K_d$ assumption. Finally, these immobile reactive tracers may sorb onto colloids, thereby enhancing their mobility.

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