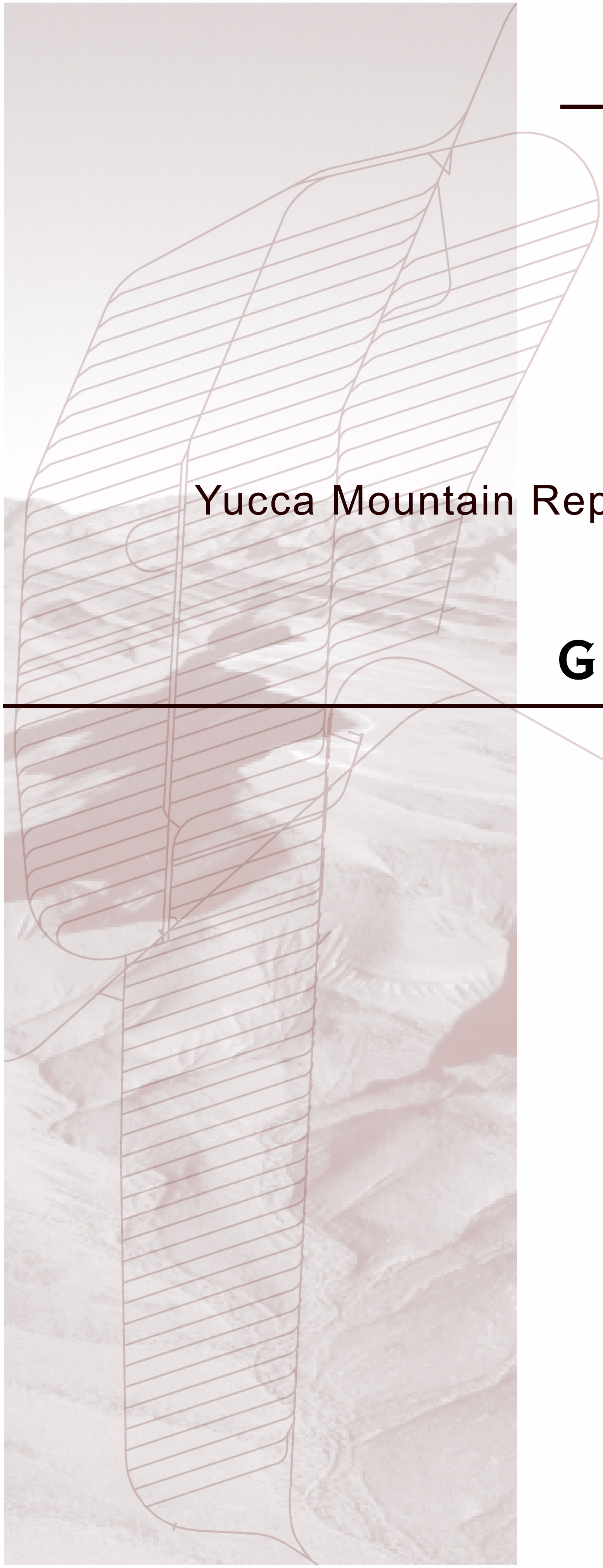

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Yucca Mountain Repository License Application

GENERAL INFORMATION

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ACRONYMS

DOE	U.S. Department of Energy
ECRB	Enhanced Characterization of the Repository Block
ESF	Exploratory Studies Facility
FEP	feature, event, or process
GROA	geologic repository operations area
HLW	high-level radioactive waste
NRC	U.S. Nuclear Regulatory Commission
PSHA	probabilistic seismic hazard analysis
PVHA	probabilistic volcanic hazard analysis
RMEI	reasonably maximally exposed individual
SNF	spent nuclear fuel
TAD	transportation, aging, and disposal
TEV	transport and emplacement vehicle
TSPA	total system performance assessment

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GLOSSARY

aging. Placing commercial spent nuclear fuel in an aging overpack on an aging pad for a long period of time (years) for radioactive decay. Radioactive decay results in a cooler waste form that ensures thermal limits are met.

barrier. Any material, structure, or feature that, for a period to be determined by the NRC, prevents or substantially reduces the rate of movement of water or radionuclides from the Yucca Mountain repository to the accessible environment, or prevents the release of radionuclides from the waste. For preclosure safety considerations, a barrier is any device or measure that decreases the likelihood of occurrence or adverse effects of a threat to safety or quality.

buffer. Short-term holding area for loaded or unloaded transportation casks prior to movement into a handling facility for processing or prior to removal from the geologic repository operations area.

confinement. A building, building space, room, cell, or other enclosed volume in which air supply and exhaust are controlled, and typically filtered.

containment. A leak-tight enclosure designed to prevent fission products from escaping to the atmosphere.

controlled access area. Any temporarily or permanently established area, which is clearly demarcated, to which access is controlled and that affords isolation of the material or persons within it.

event sequence. A series of actions and/or occurrences within the natural and engineered components of a geologic repository operations area that could potentially lead to exposure of individuals to radiation. An event sequence includes one or more initiating events and associated combinations of repository system component failures, including those produced by the action or inaction of operating personnel. Those event sequences that are expected to occur one or more times before permanent closure of the geologic repository operations area are referred to as Category 1 event sequences. Other event sequences that have at least one chance in 10,000 of occurring before permanent closure are referred to as Category 2 event sequences.

feature. A physical, chemical, thermal, or temporal characteristic of the site or potential repository system. For the purposes of screening features, events, and processes for the total system performance assessment, a feature is defined to be an object, structure, or condition that has a potential to affect repository system performance.

geologic repository operations area. A HLW facility that is part of a geologic repository, including both surface and subsurface areas, where waste handling activities are conducted.

important to safety. With reference to structures, systems, and components, those engineered features of the geologic repository operations area whose function is: (1) to provide reasonable assurance that HLW can be received, handled, packaged, stored, emplaced, and retrieved without exceeding the requirements of 10 CFR 63.111(b)(1) for Category 1 event sequences; or (2) to prevent or mitigate Category 2 event sequences that could result in radiological exposures exceeding the values specified at 10 CFR 63.111(b)(2) to any individual located on or beyond any point on the boundary of the site.

important to waste isolation. With reference to design of the Engineered Barrier System and characterization of natural barriers, those engineered and natural barriers whose function is to provide a reasonable expectation that HLW can be disposed of without exceeding the requirements of 10 CFR 63.113(b) and (c).

initiating event. A natural or human-induced event that causes an event sequence.

land ownership area. Lands that are either acquired lands under the jurisdiction and control of the DOE or lands permanently withdrawn and reserved for its use.

licensing bases. The set of NRC requirements applicable to the Yucca Mountain site and the licensee's written commitments for ensuring compliance with and operation within applicable NRC requirements and the Yucca Mountain site design basis (including all modifications and additions to such commitments over the life of the license) that are docketed and in effect. The licensing bases include the NRC regulations, orders, license conditions, exemptions, and license specifications. It also includes the Yucca Mountain site design basis information defined in 10 CFR 63.2 as documented in the most recent SAR as required by 10 CFR 63.21, 63.24, or 63.44 and the licensee's commitments remaining in effect that were made in docketed licensing correspondence such as licensee responses to NRC bulletins, generic letters, and enforcement actions, as well as licensee commitments documented in NRC safety evaluations or licensee event reports.

license condition. Any requirement or restriction imposed by the NRC as part of construction authorization or the license to receive and possess source, special nuclear, or byproduct material at Yucca Mountain. A license condition may be in the form of a condition in the body of the license or in the form of a license specification, derived from analyses and evaluations in the license application and appended to the license, that outlines the operational limits of the facility.

license specifications. A set of license conditions appended to the license to receive and possess radioactive material that outline specific operational limits of the facility. License conditions are derived from analyses and evaluations in the license application. The term "license specifications" in 10 CFR Part 63 is equivalent to the term "technical specifications" in 10 CFR Parts 50 and 72.

member of the public. Any individual except when that individual is receiving an occupational dose.

normal operations. Planned, routine activities in which closely monitored exposures are expected from the high-level radioactive waste or spent nuclear fuel processed at the geologic repository operations area.

nuclear safety design basis. Information that identifies the specific nuclear safety functions to be performed by an SSC of a facility and the specific nuclear safety values or ranges of values chosen for controlling parameters as reference bounds for design. These values may be constraints derived from generally accepted state-of-the-art practices for achieving functional goals, or they may be requirements derived from the analyses (based on calculations or experiments) of the effects of a postulated event under which an SSC must meet the functional goals. The values of controlling parameters for external events include (10 CFR 63.2): estimates of severe natural events used for deriving design bases that are based on the consideration of historical data, physical data, and analysis of the upper limits of the physical processes involved; estimates of severe external human-induced events used for deriving design bases that are based on the analysis of human activity in the region, taking into account site characteristics and risks associated with the event.

occupational dose limits. Limits on allowed occupational dose to individual adults promulgated in 10 CFR 20.1201.

off-normal events. Deviations from procedures and equipment failures that do not lead to significantly elevated exposures to occupationally exposed individuals. Off-normal events are not Category 1 events.

onsite public. Any individual within the preclosure controlled area who is not receiving an occupational dose.

other design information. All other design information not included in the nuclear safety design basis or supporting design information. Other design information includes design information necessary to achieve certain economies of operation, maintenance, procurement, installation, or construction. Other design information may be presented in the SAR (as design descriptions) or other documents docketed with the NRC or retained by the applicant or licensee.

performance confirmation. The program of tests, experiments and analysis that is conducted to evaluate the adequacy of the information used to demonstrate compliance with identified performance objectives of 10 CFR Part 63, Subpart E.

postclosure. The period of time after permanent closure of the repository system.

postclosure controlled area. (1) The surface area, identified by passive institutional controls, that encompasses no more than 300 km^2. It must not extend: (i) farther south than 36°40′13.6661″ North latitude, in the predominant direction of groundwater flow; and (ii) farther than 5 km from the repository footprint in any other direction; and (2) the subsurface underlying the surface area.

preclosure. The period of time before permanent closure of the geologic repository operations area.

preclosure controlled area. Area inside the site boundary, access to which can be limited by the licensee for any reason.

preclosure safety analysis. A systematic examination of the site; the design; and the potential hazards, initiating events, and event sequences and their consequences (e.g., radiological exposures to workers and the public). The analysis identifies structures, systems, and components important to safety.

procedural safety control. Procedures, training, maintenance, configuration control, human factor evaluations, audits and self-assessments, emergency planning, and investigation requirements, and other activities performed by personnel to ensure that operations are within analyzed condition.

protected area. An area encompassed by physical barriers and to which access is controlled.

reasonably maximally exposed individual. A hypothetical person meeting the criteria specified in 10 CFR 63.312. Criteria includes being an adult, living in the accessible environment above the highest concentration of radionuclides in the plume of contamination, having a diet and lifestyle representative of the people in the surrounding community, and using a specified amount of well water.

recovery. Actions taken after termination of the event sequence to safely recover materials or place the facility back into a safe condition.

relocation. The act of temporarily or permanently moving a waste package from one emplacement drift to another emplacement drift, or to a different emplacement location within the same drift.

removal. The act of temporarily moving a waste package from the subsurface facility to a surface facility for the purposes of inspecting, testing, or remediation. A removed waste package is put back in its intended emplacement location after the reason for its removal has been satisfied.

repository footprint. The outline of the outermost locations of where the waste is emplaced in the repository.

restricted area. Area within the controlled area, access to which is limited by the licensee for the purpose of protecting individuals against undue risks from exposure to radiation and radioactive materials.

retrieval. The act of permanently removing radioactive waste from the underground location at which the waste had been previously emplaced for disposal.

site. Area surrounding the geologic repository operations area for which the DOE exercises authority over its use in accordance with the provisions of 10 CFR Part 63.

site boundary. The line beyond which the land or property is not owned, leased, or otherwise controlled by the licensee.

staging. Short-term storage of waste forms within a facility to accommodate thermal blending or other operational needs.

supporting design information. The set of detailed design information underlying (supporting) nuclear safety design bases, including other design inputs, design analyses, and design output documents. Supporting design information may be presented in the SAR (as design description) or other documents docketed with the NRC or retained by the applicant or licensee.

termination of the event sequence. The condition at which elevated exposure conditions to persons have ended (e.g., by evacuation of personnel or physical mitigation), and the affected systems are no longer reasonably vulnerable to additional failure progression or additional failures related to the event sequence.

total system performance assessment. A risk assessment that quantitatively estimates how the proposed Yucca Mountain disposal system will perform in the future under the influence of specific features, events, and processes, incorporating uncertainty in the models and data.

unrestricted area. An area, access to which is neither limited nor controlled by the licensee.

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1. GENERAL DESCRIPTION

10 CFR 63.2 defines the geologic repository operations area (GROA) at Yucca Mountain, Nevada, as "a high-level radioactive waste facility that is part of a geologic repository, including both surface and subsurface areas, where waste handling activities are conducted." A general description of the GROA and its location, the general nature of the activities to be performed at the GROA, and the basis for the exercise of the U.S. Nuclear Regulatory Commission (NRC) licensing authority over a geologic repository are presented in Sections 1.1, 1.2, and 1.3, respectively. Section 1.4 identifies the materials incorporated by reference into this license application.

This section provides information that addresses specific regulatory acceptance criteria in Section 1.1.3 of NUREG-1804. The information presented in this section also addresses requirements contained in 10 CFR 63.21(b)(1) and 10 CFR 63.23. The following table lists the information provided in this section, the corresponding regulatory requirements, and applicable acceptance criteria from NUREG-1804.

GI Section	Information Category	10 CFR Part 63 Reference	NUREG-1804 Reference
1	General Description	63.2 63.21(b)(1) 63.23	Not applicable
1.1	Location and Arrangement of Structures, Systems, and Components of the Geologic Repository Operations Area	63.21(b)(1)	Section 1.1.3: Acceptance Criterion 1
1.2	General Nature of the Geologic Repository Operations Area Activities	63.21(b)(1)	Section 1.1.3: Acceptance Criterion 2
1.3	Basis for U.S. Nuclear Regulatory Commission Exercise of its Licensing Authority	63.21(b)(1)	Section 1.1.3: Acceptance Criterion 3(1)
1.4	General References and Materials Incorporated by Reference	63.23	Not applicable

1.1 LOCATION AND ARRANGEMENT OF STRUCTURES, SYSTEMS, AND COMPONENTS OF THE GEOLOGIC REPOSITORY OPERATIONS AREA *[NUREG-1804, Section 1.1.3: AC 1]*

Yucca Mountain is located in the western United States (Figure 1-1), on federal land in Nye County in southern Nevada, approximately 90 mi northwest of Las Vegas (Figures 1-2 and 1-3). The GROA, where waste handling activities are conducted, is located within the site, defined in 10 CFR 63.2, and within the postclosure controlled area, defined in 10 CFR 63.302 (Figure 1-4). The restricted area, defined in 10 CFR 63.2, is located within the GROA and separates waste handling operations from other activities within the GROA during phased construction.

The Yucca Mountain site is that area surrounding the GROA for which U.S. Department of Energy (DOE) exercises authority over its use in accordance with 10 CFR Part 63. This area is also designated as the preclosure controlled area defined in 10 CFR 20.1003. At closure, the site is to be identified by monuments, as described in SAR Section 5.8.

The postclosure controlled area is defined in 10 CFR 63.302 as to size, southern boundary, and distance from the repository footprint and includes the subsurface underlying the surface area. At closure, the postclosure controlled area is to be identified by passive institutional controls (markers), as described in SAR Section 5.8. The repository footprint is defined in 10 CFR 63.302 as the outline of the outermost locations of where the waste is emplaced in the Yucca Mountain repository.

The general environment is defined in 10 CFR 63.202 as "everywhere outside the Yucca Mountain site, the Nellis Air Force Range, and the Nevada Test Site," which is designated as the unrestricted area.

Facilities within the GROA are identified in Figure 1-5; surface facilities within the GROA are further identified in Figure 1-6.

1.1.1 Physical Characteristics of Repository Site and Environs

[NUREG-1804, Section 1.1.3: AC 1(1)(a)]

This section provides a general discussion of the physical characteristics of the repository site and environs important to public health and safety.

1.1.1.1 Site Location and Geography

Yucca Mountain is located in the southern Great Basin, within the Basin and Range Geological Province of the western United States (Figure 1-1). It is located on federal land in Nye County in southern Nevada, an arid region of the United States, approximately 90 mi northwest of Las Vegas (Figures 1-2 and 1-3). Additional information on geology and demography (of the site and region) is provided in Section 5.2.1 and SAR Section 1.1.2, respectively.

Yucca Mountain consists of a series of north–south-trending ridges extending approximately 25 mi from Timber Mountain in the north to the Amargosa Desert in the south. Above the location of the underground facility, the crest of Yucca Mountain reaches elevations of 4,920 to 6,330 ft above sea level. The west side of the crest is marked by an escarpment that drops approximately 1,000 ft to the base of Solitario Canyon. East of the crest, the mountain slopes gently to the east and is incised by a series of east- to southeast-trending washes. The elevation at the base of the eastern slope is approximately 1,100 to 1,500 ft below the ridge crest (Potter et al. 2002).

Facilities in the GROA (both surface and subsurface) and adjacent support facilities will be developed as shown in SAR Figure 1.1-3.

The surface facilities for the repository are situated in Midway Valley, which is east of Yucca Mountain. Elevations of the Midway Valley floor range from about 3,500 ft above sea level in the east to about 4,000 ft above sea level in the northwestern part of the valley. Yucca Wash and washes to the north and along the east slope of the Yucca Mountain channel flow eastward across Midway Valley into Fortymile Wash.

1.1.1.2 Site Geology and Hydrology

Surficial deposits in Midway Valley and the Yucca Mountain area include (Swan et al. 2001, p. 8):

- Unconsolidated sediment fans, including terrace deposits along active washes
- Debris-flow deposits along the base of the hill slopes that bound the valley
- Areas of mixed bedrock and thin unconsolidated sediment
- Windblown deposits.

Yucca Mountain consists of successive layers of fine-grained volcanic rocks called tuffs, millions of years old, underlain by older carbonate rocks. These tuffs were formed when hot volcanic gas and ash erupted and flowed quickly over the landscape or settled from the atmosphere. In instances when the temperature was high enough, the ash was compressed and fused to produce a welded tuff. Nonwelded tuffs, which occur between welded layers, were compacted and consolidated at lower temperatures.

The rock units at Yucca Mountain are classified according to geologic stratigraphy, hydrogeologic properties, and thermal-mechanical characteristics. Geologic stratigraphy is used for mapping; hydrogeologic properties are used for studies of water movement and potential radionuclide transport; and thermal-mechanical characteristics are used for evaluating rock strength, mechanical properties, and the effects of heat on mechanical properties.

The repository horizon is located in the unsaturated zone a minimum of about 690 ft (210 m) above the water table in the present-day climate (SAR Section 1.1.4.2.3). It is expected to be more than 617 ft (188 m) above the water table during wetter future climate conditions (SAR Section 2.3.2.5.2). Additional details concerning geochemical characteristics of the Yucca Mountain site are provided in Section 5.2.3.

Hydrologic engineering studies for the GROA and vicinity demonstrate that the designed drainage features are adequate to protect the GROA nuclear facilities from flooding associated with the probable maximum precipitation event. Additional details concerning hydrologic engineering studies for repository surface facilities are provided in SAR Section 1.1.

1.1.1.3 Meteorology and Climatology

Understanding the meteorology and climatology at Yucca Mountain is necessary to evaluate the amount of water available to potentially interact with the waste. Both present-day and projected future climates are characterized by mean annual precipitation rates over the full infiltration modeling domain ranging from approximately 130 to 485 mm/yr. Evaporation, transpiration, and runoff reduce the amount of precipitation that infiltrates into the unsaturated zone typically by more than 90%. Mean annual surface infiltration rates range from less than 2 to about 83 mm/yr, with the largest values in projected cooler, wetter future climates (SNL 2008, Section 6.5). Additional details concerning hydrology of the Yucca Mountain site are provided in Section 5.2.2.

1.1.2 Surface Facilities

[NUREG-1804, Section 1.1.3: AC 1(1)(b), (c), (d)]

This section provides a general description of structures, systems, and components of the surface facilities in the GROA. It also provides a general description of design features of the aboveground and belowground GROA facilities, the purposes of the facilities, and the relationships among the facilities. Additional details about the repository surface facilities and operations are provided in SAR Section 1.2. Details on the determination of which structures, systems, and components are important to safety and the steps taken for classifying structures, systems, and components as part of the overall preclosure safety analysis process are presented in SAR Section 1.9.

1.1.2.1 Major Surface Design Features

The surface portion of the GROA comprises the facilities necessary to receive, stage, age, package, and support emplacement of waste (Figures 1-5 and 1-6). The surface facilities discussed in detail in this section have a minimum design operating life of 50 years and will be removed as part of the decommissioning process. The facilities will be constructed and ready for use as shown in Figure 1-7. Decontamination and dismantlement of these facilities in anticipation of permanent closure are described in SAR Section 1.12. A South Portal development area and the North Construction Portal area are nonemplacement facilities and not part of the GROA; however, the ramps that provide ventilation air are part of the GROA. Their function is to support the development of the drifts. These are discussed in SAR Section 1.3.3. All waste emplacement operations are through the North Portal.

Initial Handling Facility—The Initial Handling Facility (Area 51A) is a facility important to safety. It is a multilevel, steel braced framed building with cast-in-place reinforced concrete cells for the canister transfer operations area. The foundation of the building is reinforced concrete mat foundation. This building is located inside the GROA and provides the capability to handle and transfer high-level radioactive waste (HLW) and naval spent nuclear fuel (SNF) canistered waste to waste packages. This facility is the only facility that will process naval SNF.

The canistered waste is delivered to the facility in transportation casks by truck and railcar conveyance. The naval SNF canisters are delivered via railcar; HLW can be delivered by railcar or legal-weight truck. The cask is unloaded from the conveyance in the Initial Handling Facility; the canister is unloaded from the cask; and empty casks are returned to the conveyance. The canister is loaded into a waste package, which is then welded closed. The sealed waste package is transferred to the transport and emplacement vehicle (TEV), which transports the waste package to the emplacement drifts within the mountain.

Waste handling activities that will take place within the Initial Handling Facility include:

- Receipt of transportation casks containing canistered HLW and canistered naval SNF
- Receipt of empty waste packages
- Preparation of transportation casks for unloading
- Transfer of the HLW and naval SNF canisters to the waste packages
- Waste package closure
- Equipment maintenance, decontamination, and related activities

- Loading the waste packages into the TEV
- Return of empty transportation cask for reuse.

Aging Facilities—The aging facilities located north of the North Portal consist of the aging pads (Area 17P and Area 17R), aging overpacks, and cask transfer equipment, which are classified as important to safety. Normally, transportation casks containing commercial SNF that requires aging in dual-purpose canisters or in transportation, aging, and disposal (TAD) canisters will be unloaded in the Receipt Facility and transferred to aging overpacks so site transporters can safely move the canisters in aging overpacks to one of the concrete aging pads for long-term thermal management. Casks containing horizontal dual-purpose canisters are moved to the transfer trailer in the Receipt Facility and from there to the aging pad where the casks are opened and the horizontal dual-purpose canister is pushed into a horizontal aging module. TAD canisters can also be transferred to the Aging Facility from the Canister Receipt and Closure Facilities and the Wet Handling Facility.

The purpose of the aging facilities is to provide safe cooling of commercial SNF within TAD canisters and dual-purpose canisters, in aging overpacks or horizontal aging modules, until the thermal heat load of the SNF has decayed to a level low enough to be placed in a waste package. The aging facility includes aging overpacks and crawler-type site transporters for moving aging overpacks containing canisters of commercial SNF between aging pads and various surface facilities.

The aging facilities will have a maximum total aging capacity of 21,000 MTHM in 2,500 aging spaces.

Central Control Center Facility—This facility (Area 240) is a balance of plant facility and is not important to safety and provides centralized control and communications for plant-wide monitoring and control. The Central Control Center and central communications room share common heating, ventilation, air-conditioning, and electrical systems. Within the Central Control Center, through the digital control and management information system, operators monitor and control select systems and monitor other surface and subsurface systems utilizing a centralized status and alarm station for the entire repository. The TEV operations on the surface and the subsurface are controlled from the Central Control Center. The Central Control Center Facility is described in SAR Section 1.2.8.1.1.4. The digital control and management information system is described in SAR Section 1.4.2.

Wet Handling Facility—The Wet Handling Facility (Area 50) is important to safety and is designed to receive commercial SNF in legal-weight truck and rail-based transportation casks and in dual-purpose canisters, which are shipped in rail-based transportation casks. Commercial SNF is transferred underwater in a pool from transportation casks and dual-purpose canisters into TAD canisters. The Wet Handling Facility includes provisions for closing loaded TAD canisters and for opening dual-purpose canisters prior to unloading. Shielded transfer casks or aging overpacks are used to move a loaded TAD canister between the various surface facilities at the GROA. The Wet Handling Facility is located on the surface, east of the North Portal.

The Wet Handling Facility provides the space, layout, structures, and systems to support commercial SNF transfer operations and closure of TAD canisters. This facility also provides a safe environment for personnel and equipment involved in commercial SNF transfer operations. The location of the Wet Handling Facility relative to the other surface facilities is shown in SAR Figure 1.2.1-2. The Wet Handling Facility has a limited-capacity, in-process waste staging area in the pool. This consists of storage racks with the capacity to hold approximately 80 pressurized water reactor SNF assemblies and 120 boiling water reactor SNF assemblies. The Wet Handling Facility has the capability to rework and/or repair canisters, casks, and dual-purpose canisters.

Waste handling activities that will take place within the Wet Handling Facility include:

- Receipt of transportation casks containing uncanistered commercial SNF assemblies
- Receipt of commercial SNF in dual-purpose canisters and off-normal commercial SNF in damaged fuel cans
- Receipt of empty TAD canisters for transfer into the pool
- Provision of space and equipment to perform repair/rework of off-normal assemblies and containers
- Provisions of space and equipment to open dual-purpose canisters and to close and seal TAD canisters
- Transfer of uncanistered SNF from dual-purpose canisters into the TAD canisters
- Transfer of uncanistered SNF from transportation casks into TAD canisters
- Enabling transfer of TAD canisters to a Canister Receipt and Closure Facility for transfer to a waste package or to the Aging Facility if required to allow for thermal decay.

Canister Receipt and Closure Facilities—There are three Canister Receipt and Closure Facilities (Area 60, Area 70, and Area 80) planned for the repository. These facilities are important to safety. The Canister Receipt and Closure Facilities provide the space, radiological confinement, structures, and internal systems that support stand-alone canister handling operations. The locations of the Canister Receipt and Closure Facilities are shown in SAR Figure 1.2.1-2. The Canister Receipt and Closure Facilities contain structures, systems, and components that are capable of receiving and handling HLW canisters, DOE SNF canisters (not including naval SNF), and commercial SNF in TAD canisters; placing them into waste packages; closing the waste packages; and transporting them to be disposed of in emplacement drifts. Damaged canisters and waste packages will be sent to the Wet Handling Facility to allow repair or rework, or both, to be done if repair cannot be completed in the Canister Receipt and Closure Facility. The Canister Receipt and Closure Facilities also have the capability to receive dual-purpose and TAD canisters and transfer them to aging overpacks.

Waste handling activities that will take place within the Canister Receipt and Closure Facilities include:

- Transportation cask unloading and waste package preparation and transport
- Receipt of empty waste packages for processing
- Enabling movement of TAD canisters and dual-purpose canisters in aging overpacks to the Aging Facility
- Enabling movement of canisters to other facilities in aging overpacks
- Transfer of canisters to waste packages
- Waste package closure
- Loading of completed waste package into TEV
- Equipment maintenance, radiological surveys, decontamination, and low-level radioactive waste collection
- Return of empty transportation cask for reuse.

Low-Level Waste Facility—The Low-Level Waste Facility (Area 160) is a balance of plant facility that is not important to safety. It is a one-level building with a mezzanine floor designed to accept, manage, and store dry active waste until bulk shipment to an offsite vendor for processing and liquid radioactive waste until it is processed. The building design provides for interim storage of packaged waste received on a routine basis from the GROA nuclear facilities. Storage space is provided for various site-produced waste forms which will include dry active wastes and Wet Handling Facility pool filters that may be in drums or other appropriate containers, and empty dual-purpose canisters. For storage outside the facility, concrete pads are attached adjacent to the storage bays.

Receipt Facility—The purpose of the Receipt Facility (Area 200) is to provide safe and controlled operating areas for receiving and transferring rail-based transportation casks containing TAD canisters or dual-purpose canisters, preparing the transportation casks for transfer, and transferring the TAD canisters or dual-purpose canisters from the transportation cask to an aging overpack. The TAD canisters and dual-purpose canisters are transferred, using dry shielded transfer, from transportation casks to an aging overpack for movement to the Canister Receipt and Closure Facility, the Wet Handling Facility, or the aging pads. Transportation casks containing horizontal dual-purpose canisters are transferred to the transfer trailer in the Receipt Facility and moved to the aging pads where the cask is opened and the horizontal dual-purpose canister is pushed into a horizontal aging module. The Receipt Facility also prepares unloaded transportation casks and railcar conveyances for return to the national transportation system. The Receipt Facility is located north of the North Portal. The location of the Receipt Facility is shown in SAR Figure 1.2.1-2. The Receipt Facility's main structure and many of the components within the structure are classified as important to safety.

Waste handling activities that will take place within the Receipt Facility include:

- Receipt of transportation casks containing commercial SNF in TAD canisters or dual-purpose canisters
- Transportation cask unloading
- Aging overpack closure
- Equipment maintenance, radiological surveys, and decontamination.

Emergency Diesel Generator Facility—The Emergency Diesel Generator Facility (Area 26D) is a balance of plant facility that is not important to safety. It is a one-story structure whose base slab, walls, and roof are constructed of reinforced concrete.

The Emergency Diesel Generator Facility provides space for two emergency diesel generators (Train A and Train B) and two day tanks in the generator room, 13.8-kV switchgear in the switchgear room, and battery rooms. During a loss of normal offsite electrical power, the Emergency Diesel Generator Facility is designed to provide continuous 13.8-kV power to power load demands important to safety in four waste handling facilities (i.e., Canister Receipt and Closure Facilities 1, 2, and 3; and the Wet Handling Facility).

Miscellaneous Repository Facilities—Miscellaneous repository facilities directly or indirectly support repository infrastructure and operating systems. SNF and HLW handling operations are not performed in these facilities. The miscellaneous facilities also interface with waste emplacement facilities. Miscellaneous facilities do not include repository subsurface areas.

The miscellaneous facilities also interface with offsite services and functions, such as the primary site access road, service roads, the South Portal, the North Construction Portal, and utility structures. They do not include railroad transportation infrastructure, systems, or components beyond the designated point of the repository-to-transportation interface. The miscellaneous facilities also support repository construction by furnishing power and water, communication networks, and emergency response capabilities.

The miscellaneous plant facilities include:

- **Warehouse and Non-Nuclear Receipt Facility**—The Warehouse and Non-Nuclear Receipt Facility (Area 230) stores empty waste packages, lids, and pallets until needed.
- **Facilities for Utilities Area**—The facilities for utilities (Area 25) include individual facilities and areas that provide functional space and layout for plant services, electrical power distribution and support, storage of service gases (including nitrogen, helium, and argon), firewater facilities, an evaporation pond, and a cooling tower. The mechanical services systems and equipment that support repository operations are housed in a separate Utilities Facility. These include equipment for the heating and cooling systems, water systems, instrument air and compressed air systems, and service gas systems.

- **Emergency Response Facilities**—The emergency response facilities (Area 63A) include a fire, rescue, and medical facility. The fire, rescue, and medical facility is a multifunctional facility that provides space and layout for fire protection and fire-fighting services, underground rescue services, and emergency and occupational medical services.

- **Materials and Consumable Facilities**—The Warehouse/Central Receiving (Area 68A) provides functional space for warehousing and receiving materials. The materials/yard storage (Area 68B) provides functional space for storing materials. The equipment yard/storage (Area 71B) provides functional space for storing equipment.

- **Maintenance and Repair Facilities**—The maintenance and repair facilities include the Heavy Equipment Maintenance Facility (Area 220) and the craft shops (Area 71A) and provide space and layout for craft shops, heavy equipment maintenance, and vehicle maintenance (Area 690).

- **Security Facilities**—The security facilities include the Central Security Station (Primary Alarm Station) (Area 30), administration security stations (Area 65A and Area 65B), Cask Receipt Security Station (Secondary Alarm Station) (Area 30B), and North Perimeter Security Station (Area 30C).

Details of the miscellaneous plant facilities are provided in SAR Section 1.2.8.

1.1.2.2 Surface Facilities to Be Dismantled Prior to Decommissioning and Closure

An application for a license amendment will be submitted to the NRC before permanent closure of the repository in accordance with 10 CFR 63.51. At that time, a determination will be made that the surface facilities are no longer required to support SNF and HLW handling, processing, emplacement, or retrieval. Upon NRC approval of the application, the surface facilities, except for permanent monuments and markers, will be decontaminated, decommissioned, and dismantled. Design considerations to facilitate permanent closure and dismantlement are discussed in SAR Section 1.12.

During the design process, structures, systems, and components are reviewed for decontamination and dismantlement considerations to ensure that features that support waste minimization and worker safety are incorporated and as low as is reasonably achievable principles are considered for decontamination and dismantlement activities.

These features include:

- Selection of materials and processes to minimize waste production

- Minimizing materials that are susceptible to neutron activation to minimize production of radioactive waste

- Use of construction materials and surface finishes to minimize porosity, crevices, and rough machine marks on structures, systems, and components to limit the potential for contamination and facilitate ease of decontamination

- Stainless-steel-lined wet handling pool with a leak-detection drainage system to minimize the contamination of concrete around the pool
- Use of confinement systems to contain and minimize the spread of potential airborne radioactive contamination
- Incorporation of features to contain leaks and spills
- Use of exhaust ducting and high-efficiency particulate air filters for the exhaust ventilation system of areas or rooms that may become contaminated.

More details on the decontamination and dismantlement considerations are described in SAR Section 1.12.

Plans for decontamination, dismantlement, deconstruction, and permanent closure of the surface facilities, along with implementation of NUREG-1757 (Banovac et al. 2006; Schmidt et al. 2006; Fredrichs et al. 2003), are discussed in SAR Section 1.12.

At permanent closure, a network of permanent monuments and markers will be erected. The monuments and markers are intended to warn future generations of the presence and nature of the buried waste, and will include perimeter monuments, warning markers, and site monuments. The monument and marker network is discussed in SAR Section 5.8.

1.1.3 Subsurface Facilities

[NUREG-1804, Section 1.1.3: AC 1(1)(b), (c), (d)]

This section provides a general description of subsurface facilities in the GROA, design features of the aboveground and belowground facilities, the purposes of the facilities, and the relationships among the facilities. Additional details about the GROA subsurface facilities and operations are provided in SAR Section 1.3. Facilities described herein are permanent facilities, phased to be operational in accordance with the sequence described in Section 2.

1.1.3.1 Major Subsurface Design Features

The subsurface GROA (Figure 1-5) consists of the features and facilities necessary to transport and emplace waste packages and provide ventilation to the emplaced waste packages. These subsurface features and facilities include excavated drifts, rail lines, waste package emplacement pallets, engineered inverts, and support systems.

Waste packages supported on waste package emplacement pallets, which, in turn, are supported by drift inverts, are emplaced in emplacement drifts. Features associated with the emplacement drifts, including waste packages, waste package emplacement pallets, emplacement drift inverts, and drip shields, are described below.

Emplacement Drifts—The emplacement drifts are large circular tunnels, nominally 18 ft in diameter, used to provide emplacement for 70,000 MTHM of waste contained in about 11,000 waste packages (SAR Sections 1.3.2.4 and 1.3.4.2.3). The total subsurface emplacement area required to accommodate the waste packages is about 1,250 acres (BSC 2007). This area includes approximately 40 mi of emplacement drifts excavated by tunnel boring machines. The drifts are built in a series of panels phased to accommodate the planned receipt of waste (Section 2). In addition to emplacement drifts, Panel 1 includes up to two drifts dedicated to performance confirmation testing plus an associated observation drift. Ground support is installed behind the tunnel boring machine excavators to provide structural support and worker protection.

The emplacement drift inverts consist of engineered steel structures and fill materials at the base of the emplacement drifts. The inverts support the pallets, waste packages, drift rail system, and drip shields. Details of the drift and invert design are provided in SAR Section 1.3.4.

The GROA has several types of nonemplacement excavations:

- **Access Mains**—These drifts are large circular tunnels, nominally 25 ft in diameter, used to provide access to the emplacement drifts.

- **Exhaust Mains—**These drifts are nominally 25 ft in diameter and are used to exhaust ventilation air from the emplacement drifts.

- **Turnouts**—Turnouts are curved sections of tunnel connecting the emplacement drifts to the access mains. The turnouts are nominally 18 ft in diameter. The turnout configuration also shields the main drift from radiation associated with emplaced waste packages.

- **Performance Confirmation Observation Drift**—This drift, which provides access to the monitoring instrumentation stations and alcoves, is similar in cross-sectional area to the emplacement drifts and is located at an elevation below the performance confirmation test drifts.

- **Alcoves**—Alcoves serve various purposes, such as serving as equipment or instrumentation chambers and refuge chambers to provide a safe haven for personnel in the event of degraded environmental conditions. There will be a performance confirmation alcove, the openings of which are located in the nonemplacement area, and which will be used for deploying instrumentation and equipment for monitoring the host rock in the vicinity of the initial emplacement drifts in Panel 1 (SAR Sections 1.3.3.1.6 and 1.3.3.1.7).

- **Ventilation Shafts**—The ventilation shafts connect the subsurface with the surface and are used to intake and exhaust air to meet thermal management goals. The shafts are typically circular vertical openings approximately 24 ft in excavated diameter (SAR Section 1.3.3).

Waste Packages—The waste package consists of a single design with six configurations. The different waste package configurations have multiple internal structures and different external dimensions to allow acceptance of various waste forms. The waste forms received and packaged for disposal are canistered SNF in TAD canisters; canistered SNF owned by the DOE, including canistered naval SNF; and canistered HLW from prior commercial and defense fuel reprocessing operations. Some commercial SNF, including DOE SNF of commercial origin, may be received as uncanistered SNF in a cask. Some commercial SNF may also be received in dual-purpose canisters.

The six configurations are as follows:

- 21-PWR/44-BWR TAD waste package
- 5-DHLW/DOE Short Codisposal
- 5-DHLW/DOE Long Codisposal
- 2-MCO/2-DHLW
- Naval Short
- Naval Long.

The waste package consists of two concentric cylinders in which the waste forms are placed. The inner vessel includes the inner cylinder, bottom inner lid, and top inner lid. The outer corrosion barrier includes the outer cylinder, bottom outer lid, and top outer lid. The inner vessel is Stainless Steel Type 316 (UNS S31600), modified with additional constraints on the nitrogen and carbon content. The outer corrosion barrier is Alloy 22 (UNS N06022) (with some restrictions on the range of alloying elements), a corrosion-resistant, nickel-based alloy.

The two closure lids are the top inner lid for the inner vessel and the outer corrosion barrier top outer lid, and they provide a leak-tight closure. The outer lid is made of Alloy 22. The inner lid is modified Stainless Steel Type 316. The inner lid has a small purge port to allow purging and fill-gas ingress.

After the inner lid has been installed and before the Stainless Steel Type 316 inner vessel is sealed, the waste package is evacuated, and helium is added as an inert fill gas through the purge port. The helium helps transfer heat from the waste form to the wall of the inner vessel. Once the vessel is filled with helium and successfully leak tested, the port is plugged and welded shut.

The closure methods for the inner and outer lids differ. The inner stainless steel lid is held in place by a spread ring and is seal welded. The outer Alloy 22 lid is narrow-groove welded with plasticity burnishing for stress mitigation. The welds are made by a robotic cold-wire-feed gas tungsten arc welding method. The SNF and HLW transfer system and the waste package closure system are described in SAR Section 1.2. A description of the waste package and waste forms is provided in SAR Section 1.5.2.

Each waste package is structurally supported by a pallet in an emplacement drift. Emplacement pallets, fabricated from the same materials as the waste packages, are themselves supported by the emplacement drift invert. Emplacement pallet design details are provided in SAR Section 1.3.

Drip Shields—Titanium drip shields will be installed, during closure activities, to protect waste packages from dripping water and rockfall during the postclosure period. Drip shield design details are provided in SAR Section 1.3.4.

1.1.3.2 Subsurface Facilities to Be Dismantled prior to Closure

The final phase of the repository preclosure period is the closure of the subsurface facility. Closure consists of the following activities (SAR Section 1.3.6.1):

- Installation of drip shields
- Removal of noncommitted materials from the subsurface facility
- Placement of backfill in ramps and shafts
- Dismantlement of ventilation shaft collar surface fans, ductwork, and other appurtenances
- Regrading of affected areas and installation of surface monuments
- Final site restoration.

Installation of the drip shields will be initiated after a license amendment to close the repository has been approved by the NRC.

The closure process involves removal of previously installed items outside of the emplacement drifts that have an impact on long-term repository performance. These items can include concrete, air doors, electrical cables, and rail. SAR Section 1.12 provides criteria, methodologies, and approaches to be used for planned decontamination and dismantlement activities, and management of residual radioactive waste streams for site decommissioning. SAR Section 1.3.6 provides more detail on removal of noncommitted subsurface materials and subsurface facility closure.

1.1.4 Plans to Restrict Access to and Regulate Land Uses around the Geologic Repository Operations Area

[NUREG-1804, Section 1.1.3: AC 1(1)(e)]

The Yucca Mountain site is located in Nye County, Nevada. Nye County is bordered by Clark, Lincoln, White Pine, Eureka, Lander, Churchill, Mineral, and Esmeralda counties in Nevada (Figure 1-3) and Inyo County in California. The federal government currently controls the vast majority of the land in the region. The area needed for the repository encompasses land controlled by three federal agencies: the U.S. Department of Defense (the Nevada Test and Training Range, formerly known as the Nellis Air Force Range), the Bureau of Land Management, and DOE agencies, which include the National Nuclear Security Administration (Nevada Test Site). The GROA and supporting areas, utilities, and roads are expected to require the active use of as much as 2,050 acres of land. Of this total area, about 370 acres have been visibly disturbed by site characterization and related activities (DOE 2002, Section 2.1.2).

The GROA will be located in and on lands that are either acquired lands under the jurisdiction and control of the DOE or that are permanently withdrawn and reserved for DOE use. Details regarding controls to restrict access and regulate land use in and around the GROA are discussed in SAR Section 5.8.

At permanent closure, a network of permanent monuments and markers will be erected to warn future generations of the presence and nature of the buried waste. Detailed public records will identify the location and layout of the repository and the hazardous nature of the waste it contains. Plans for repository permanent closure are presented in SAR Section 1.12. The monument and marker network is discussed in SAR Section 5.8.

1.1.5 Radiological Monitoring and Plans for Mitigation of Radiological Impacts Associated with Construction and Operations

[NUREG-1804, Section 1.1.3: AC 1(1)(f)]

1.1.5.1 Radiological Monitoring

Radiological monitoring activities are described in SAR Section 5.11. As discussed in that section, the requirements for types of instruments necessary to support safe radiological operations and emergency response actions will be described in the Operational Radiation Protection Program (SAR Section 5.11). The area radiation, continuous air, and airborne radioactivity effluent monitors provide local display and alarms, as well as supply data and status information to the digital control and management information system. The process and area radiation monitoring equipment and instruments that are part of the repository are described in SAR Section 1.4.2.

An area will be set aside for the Operational Radiation Protection Program to support monitoring of radiological work, facility radiological conditions, radiological access control, and generation of radiation work controls or permits. These facilities will include provisions for contamination control, contaminated equipment storage, radioactive material storage areas, access control stations, protective clothing and change facilities, and respiratory protection equipment facilities (SAR Section 5.11.2.3).

1.1.5.2 Plans for Mitigation of Radiological Emergency Events

SAR Section 5.7 describes the Emergency Plan and addresses potential radiological emergency events during the operational life of the repository. The Emergency Plan will describe the means to mitigate consequences of each type of radiological accident. Such descriptions include:

- Equipment and design features relied upon to mitigate emergency events
- General actions that may be taken by site personnel to mitigate emergency events
- Identification of individuals responsible for activating the emergency response organization and for performing timely notifications under accident conditions
- Protective actions, including radiological protective actions, to be taken to protect the health and safety of workers and the public
- Arrangements to be made for underground and surface first-aid, medical, and hospital services
- Facilities available to support mitigation efforts, including the onsite Emergency Operations Center, the offsite Emergency Management Center, and the offsite Joint Information Center

- Response and communication equipment available to support mitigation efforts and the location of that equipment
- Provisions to periodically inventory, test, and maintain equipment.

Fixed and portable radiation and contamination monitoring instruments will be used to monitor personnel during off-normal operations and accident or emergency situations. Offsite dose calculations will include the capability of evaluating the potential radiological consequences of actual and potential radioactive effluent releases during emergency conditions.

1.2 GENERAL NATURE OF THE GEOLOGIC REPOSITORY OPERATIONS AREA ACTIVITIES

[NUREG-1804, Section 1.1.3: AC 2]

Proposed schedules for construction, receipt, and emplacement of waste are described in Section 2. A summary time line of proposed repository operations is shown in Figure 1-7. This time line depicts milestones from initial facility operations to license termination and repository closure.

1.2.1 Waste Forms to Be Disposed

[NUREG-1804, Section 1.1.3: AC 2(1)]

Commercial SNF (consisting of radioactive fuel assemblies that have been discharged from nuclear power reactors), DOE SNF (including naval SNF), and HLW are planned for disposal at the repository.

The majority of the SNF consists of commercial SNF, which comprises approximately 63,000 MTHM of the 70,000 MTHM inventory currently allowed by law. Approximately 292,000 commercial SNF assemblies (consisting of 167,000 boiling water reactor assemblies and 125,000 pressurized water reactor assemblies) (CRWMS M&O 1999, Section 3.1, Tables 3 and 4) are expected to be generated by 2040. About 221,000 of these assemblies will be placed into approximately 7,500 TAD canisters before emplacement in the repository as summarized in Table 1.5.1-1. The Wet Handling Facility would be used for dual-purpose canister processing and uncanistered commercial SNF shipped in casks.

DOE SNF represents an inventory of approximately 2,500 MTHM (DOE 2002, Table A-20). Of that inventory, approximately 160 MTHM is of commercial origin (Z, Inc. 2000, Tables 2 and 3), and is included in the 63,000 MTHM commercial allocation, leaving a DOE SNF inventory of about 2,333 MTHM (including 65 MTHM of naval SNF) which is equal to the DOE SNF allocation. This information is summarized in Table 1.5.1-1. The description of DOE SNF standardized canisters and multicanister overpacks, ranging in number from 2,500 to 5,000 (with a nominal value of 3,500), is discussed in detail in SAR Section 1.5.1.3. The description of the 400 naval SNF canisters is discussed in detail in SAR Section 1.5.1.4.

About 22,000 canisters of HLW will be generated by 2035. Currently, there are 275 canisters of HLW from reprocessed commercial SNF at the West Valley Demonstration Facility which come out of the 63,000 MTHM commercial allocation. The majority of HLW comes from the defense nuclear program (DOE 2002, Appendix A), of which a small quantity (approximately 900 canisters) may also contain cans of vitrified glass containing plutonium arrayed within the vitrified HLW. The DOE HLW allocation is 4,667 MTHM, representing approximately 9,334 HLW canisters. The West Valley and DOE HLW inventory are summarized in Table 1.5.1-1.

1.2.2 Routine Operations
[NUREG-1804, Section 1.1.3: AC 2(2)]

The GROA surface facilities have been designed to support a mostly canistered waste stream. A TAD canister is utilized for commercial SNF assemblies. The repository objective is to have 90% of individual commercial SNF assemblies loaded into TAD canisters by the utilities with a limited quantity of uncanistered individual commercial SNF assemblies and dual-purpose canisters requiring handling in a pool (i.e., submerged). In some cases, commercial SNF will require aging before it is ready for emplacement.

An operations summary time line is provided in Figure 1-7. A graphic conceptualizing the waste handling process is shown in Figure 1-8.

Canistered waste (HLW and naval SNF) is delivered to the Initial Handling Facility in transportation casks. The naval SNF canisters will be delivered via railcar; HLW will be delivered by railcar or legal-weight trucks. Equipment in the Initial Handling Facility unloads the cask from the conveyance, removes the canister from the cask, and places the empty cask back onto the conveyance. The canister is loaded into a waste package, which is welded closed. The sealed waste package is transferred to the TEV, which transports the waste package to the emplacement drifts within the mountain.

The Wet Handling Facility will process the limited number of uncanistered commercial SNF assemblies received from utilities and DOE sites. The uncanistered assemblies will be received in dual-purpose canisters and transportation casks. The dual-purpose canisters will be opened and the commercial SNF inside will be transferred under water to TAD canisters or staging racks in the pool. Uncanistered commercial SNF shipped in casks will also be transferred underwater to TAD canisters or staging racks. Once the assemblies are loaded into the TAD canister, the TAD canister, in a shielded transfer cask, will be removed from the pool and transferred to the TAD closure station. Once in the TAD closure station, a portion of the water in the TAD canister is removed to allow welding of the inner lid. Once the inner lid is sealed, the remaining water internal to the TAD canister is displaced with helium and the internal volume of the TAD canister is dried. Once dried, the canister is backfilled with helium, the vent and drain connections are sealed, and the outer lid is welded on. Upon completion of these steps, the closed TAD canister is transferred, by a canister transfer machine, from the shielded transfer cask to an aging overpack for transfer to a Canister Receipt and Closure Facility for loading into a waste package for disposal or for transfer to an aging pad.

In addition to the ability to receive and process TAD canisters from the Wet Handling Facility, Canister Receipt and Closure Facilities are designed to receive loaded canisters in aging overpacks from the aging pads, and transportation casks containing TAD canisters, HLW canisters, and DOE SNF canisters from the rail or truck staging. Finally, the Canister Receipt and Closure Facility is designed to transfer canisters from transportation casks, shielded transfer casks, and aging |

overpacks into waste packages for emplacement. Waste packages are then loaded onto the TEV for emplacement in the drifts.

The Receipt Facility expands the capability of the repository for receiving and transferring rail-based transportation casks containing TAD canisters or dual-purpose canisters, preparing the transportation casks for transfer, and transferring the TAD canisters or dual-purpose canisters from the transportation cask to a vertical aging overpack. Casks containing horizontal dual-purpose canisters are transferred to the transfer trailer in the Receipt Facility and from there to the aging pads, where the casks are opened and the horizontal dual-purpose canisters are pushed into the horizontal aging modules. The TAD canisters and dual-purpose canisters are transferred, using dry shielded transfer, from transportation casks to aging overpacks for movement to the Canister Receipt and Closure Facility, the Wet Handling Facility, or the aging pads. The Receipt Facility also prepares unloaded transportation casks and railcar conveyances for return to the national transportation system.

Concurrent Construction and Operation—The construction and operational schedule as shown in Section 2 requires the concurrent performance of construction activities and repository nuclear operations. To ensure the safety of project personnel and operational security, it will be necessary to separate these activities. During the construction process, separation is maintained by designing independent systems for repository operations and construction. This includes sufficient physical space between construction and operation activities to prevent impact. Protected area boundaries with physical barriers and isolation zones isolate personnel movement between nuclear operations and construction areas.

The emplacement operations take place in finished emplacement drifts at the same time that emplacement drifts are being constructed in other underground areas behind physical barriers. During construction, isolation bulkheads and separate ventilation systems between the development side (i.e., drifts under construction) and the emplacement side (i.e., the drifts where waste packages are being emplaced) minimize the risk of worker exposure to radiation from the waste and ensure the protection of emplaced waste packages from construction hazards. Air pressure on the development side is maintained higher than the pressure on the emplacement side in order to prevent potential airborne radioactive contamination movement from the emplacement side to the development side. Construction personnel and material do not enter the underground facility through portals and mains used to move waste packages underground. Drift construction is supported by facilities outside of the GROA, such as the South Portal development area and the North Construction Portal area.

1.2.3 Inspection and Testing of Waste Forms and Waste Packages

[NUREG-1804, Section 1.1.3: AC 2(3)]

During the handling of waste forms in the surface facilities, the types of tests and inspections to be performed related to waste forms and the waste package are described below:

- In the Receipt Facility, a visual inspection and radiological survey of the exterior of incoming transportation casks are conducted to ensure acceptable cask structural conditions and to determine any need for cleaning or decontamination:
  - Visual inspection and radiological surveys of the exteriors of incoming casks
  - Sampling of cask internal gases (if required).
- In the Initial Handling Facility and the Canister Receipt and Closure Facilities, the following activities occur to verify the structural and surface conditions of canisters and waste packages, as well as determine the radiological levels of container content and the extent of potential surface contamination:
  - Visual inspection and radiological surveys of the exteriors of incoming casks
  - Sampling of cask internal gases (if required)
  - Nondestructive examination of waste package closure welds
  - Remote visual inspection of closed waste packages.
- In the Wet Handling Facility, the following activities occur to verify the structural and surface conditions of waste forms and containers, as well as determine the radiological levels of container content and the extent of potential surface contamination:
  - Visual inspection and radiological surveys of the exteriors of incoming casks
  - Sampling of cask internal gases
  - Sampling of dual-purpose canister internal gases
  - Nondestructive examination of TAD canister closure welds.

1.2.4 Waste Retrieval Requirements

[NUREG-1804, Section 1.1.3: AC 2(4)]

This section summarizes the analysis provided in SAR Section 1.11.

The GROA is designed to permit retrieval of any or all emplaced waste, starting at any time up to the beginning of permanent closure. Retrieval operations could result from a demonstration by the Performance Confirmation Program that the postclosure regulatory standard may not be met or a policy decision to recover the economically valuable contents of SNF or to dispose of waste in a different manner. For planning purposes, it is assumed that closure and decommissioning activities begin approximately 10 years prior to closure.

The Performance Confirmation Program monitors subsurface conditions and performs tests to confirm geotechnical and design assumptions to provide information to allow actions to preserve the retrievability option. The design approach to satisfy this requirement is to ensure the repository design and emplacement operations do not preclude the retrieval of any or all waste packages prior to closure of the repository. Retrieval, as defined in 10 CFR 63.2, is "the act of permanently removing radioactive waste from the underground location at which the waste had been previously emplaced for disposal."

If a retrieval decision is made, waste would be placed in a storage or disposal facility designed in accordance with the regulations that are applicable at the time. GROA aging pads with space for up to 2,500 waste packages, SNF or HLW, are available for retrieved material but would require a specially designed waste package overpack. Ample additional space within or near the GROA is available to develop waste package storage, as needed.

Additional information pertaining to retrieval and alternate storage is provided in SAR Section 1.11.

1.2.5 Repository Closure

[NUREG-1804, Section 1.1.3: AC 2(5)]

After repository operations and the Performance Confirmation Program have been completed, the DOE will file an application with the NRC for a license amendment to close the repository. Only after the license amendment has been received from the NRC can the repository be permanently closed. 10 CFR 63.51(a)(2) and (3) require that the DOE undertake measures to regulate or prevent activities that could impair long-term waste isolation and that the repository institute a monitoring program after permanent closure. As described above, in accordance with 10 CFR 63.51, a network of permanent monuments and markers will be erected in various areas at the site to warn future generations of the presence and nature of the buried waste, and detailed public records will identify the location and layout of the repository and the hazardous nature of the waste it contains (SAR Section 5.8). Plans for permanent closure are described in SAR Section 1.12.

1.2.6 Uses of the Geologic Repository Operations Area for Purposes Other than Disposal of High-Level Radioactive Waste

[NUREG-1804, Section 1.1.3: AC 2(6)]

Although the DOE does not intend to use the GROA for purposes other than the disposal of SNF and HLW, other uses of the GROA could include Native American cultural activities, independent performance monitoring by groups other than the NRC and the DOE, and activities related to the protection of flora and fauna. The DOE will ensure that Native American cultural uses of portions of the repository site or, if approved, the GROA, will not endanger the health and safety of participants, workers, or the public and that such uses will not adversely affect structures, systems, and components that are important to safety or the natural and engineered barriers important to waste isolation. Additional details concerning control of such activities are provided in SAR Section 5.9.

1.2.7 Plans for Emergency Responses
[NUREG-1804, Section 1.1.3: AC 2(7)]

As required by 10 CFR 63.161, the DOE is developing an Emergency Plan to respond to radiological accidents. The plan is being developed in accordance with criteria contained in 10 CFR 72.32(b).

The Emergency Plan will include the following categories of information:

- A description of the responsibilities for developing, maintaining, and updating the Emergency Plan
- A description of the GROA and supporting facilities and structures
- A description of the types and classifications of potential accidents
- A description of the means for detecting initiating events and accident conditions applicable to each potential accident
- A description of the means to mitigate consequences of each type of accident
- A description of the radiological sampling and monitoring methods that will be used to assess the extent of radiological releases, as well as the instrumentation, equipment, and approved procedures that will be used to assess the extent of radioactive releases
- A description of the roles and responsibilities of personnel during an emergency
- A description of the notification and coordination procedures
- A description of the types of information to be communicated to offsite response organizations and the NRC
- A description of facility personnel training on responding to emergencies
- A description of the means for restoring the facility to a safe condition
- A description of exercise and drill activities
- A certification that the facility has complied with the requirements of the Emergency Planning and Community Right-to-Know Act of 1986 (42 U.S.C. 11001 et seq.)
- Provisions for advanced arrangements with offsite organizations
- A description of arrangements for providing timely information to the public in the event of an emergency.

A description of the Emergency Plan is provided in SAR Section 5.7.

1.3 BASIS FOR U.S. NUCLEAR REGULATORY COMMISSION EXERCISE OF ITS LICENSING AUTHORITY

[NUREG-1804, Section 1.1.3: AC 3(1)]

Congress established the bases for NRC licensing of a repository at Yucca Mountain. Section 202(3) of the Energy Reorganization Act of 1974, as amended (42 U.S.C. 5801 et seq.), authorized the NRC to exercise its licensing and regulatory authority under the Atomic Energy Act of 1954, as amended (42 U.S.C. 2011 et seq.), to license and regulate a DOE facility for the disposal of HLW, including SNF. Subsequently, Section 121(b) of the Nuclear Waste Policy Act of 1982, as amended (42 U.S.C. 10101 et seq.), authorized the NRC to promulgate technical requirements and criteria that it would apply to determine whether to approve or disapprove of DOE applications to construct a repository, receive and possess HLW and SNF in a repository, and close and decommission a repository. NRC technical requirements and criteria were to be consistent with the standards that the Environmental Protection Agency were authorized to promulgate under Section 121(a) of the Nuclear Waste Policy Act (42 U.S.C. 10101 et seq.).

In 1992, Congress passed the Yucca Mountain Development Bill, Public Law No. 107-200, 116 Stat. 735, which approved the site at Yucca Mountain, Nevada, as the candidate site for the location of a HLW repository.

In 2001, the NRC issued its technical requirements and criteria in 10 CFR Part 63. They were consistent with the Public Health and Environmental Radiation Protection Standards for Yucca Mountain, NV in the Environmental Protection Agency's 40 CFR Part 197. The NRC also determined, on several occasions, that some of its other regulatory requirements were required to be modified to apply to specific aspects of the repository. In 2004, the U.S. Court of Appeals for the D.C. Circuit upheld all of the Environmental Protection Agency's standards and the NRC rule except for the part that dealt with the time period for which waste disposal would be analyzed. When the Environmental Protection Agency finalizes its revised rule to conform to the U.S. Court of Appeals' decision, the NRC is expected to appropriately revise 10 CFR Part 63.

The NRC determination that the DOE license application satisfies all of the requirements of 10 CFR Part 63, as well as all of the other NRC regulatory requirements applicable to the repository, constitutes an adequate basis for NRC exercise of its statutory licensing authority.

1.4 GENERAL REFERENCES AND MATERIALS INCORPORATED BY REFERENCE

1.4.1 General References

General references are references that are not part of the license application. Instead, they provide background information or additional detail that will facilitate review of the application. General references may be environmental studies, technical reports, system description documents, facility description documents, or selected calculations, and they may be referenced in whole or in part. Codes and standards are also considered general references. References to such information may be located at specific points in the license application or SAR or may be listed at the end of the SAR sections or in introductory sections to the SAR.

1.4.2 Materials Incorporated by Reference

The license application consists of General Information, a Safety Analysis Report, and the Naval Nuclear Propulsion Program Technical Support Document. The Technical Support Document is submitted under separate cover because it contains classified naval nuclear propulsion information protected under federal law and regulation. Materials incorporated by reference in the license application are listed in Table 1-1. The document listed in Table 1-1 is publicly available in accordance with the requirements of 10 CFR 63.23.

In addition to the protected information noted above, some of the materials referenced in the license application may contain information that is required to be withheld from public disclosure under applicable exemptions set forth in the Freedom of Information Act (5 U.S.C 552). In those cases, the summary descriptions provided in the license application and identified in cross-references contain only that information appropriate for public disclosure.

1.5 GENERAL REFERENCES

Atomic Energy Act of 1954. 42 U.S.C. 2011 et seq.

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Table 1-1. Materials Incorporated by Reference

No.	**Description**	**Revision Number and Date**	**Date Submitted to the NRC**
1	*Quality Assurance Requirements and Description*, DOE/RW-0333P (DOE 2008)	Rev 20 2008	February 5, 2008

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Figure 1-1. Location of Yucca Mountain in the Great Basin

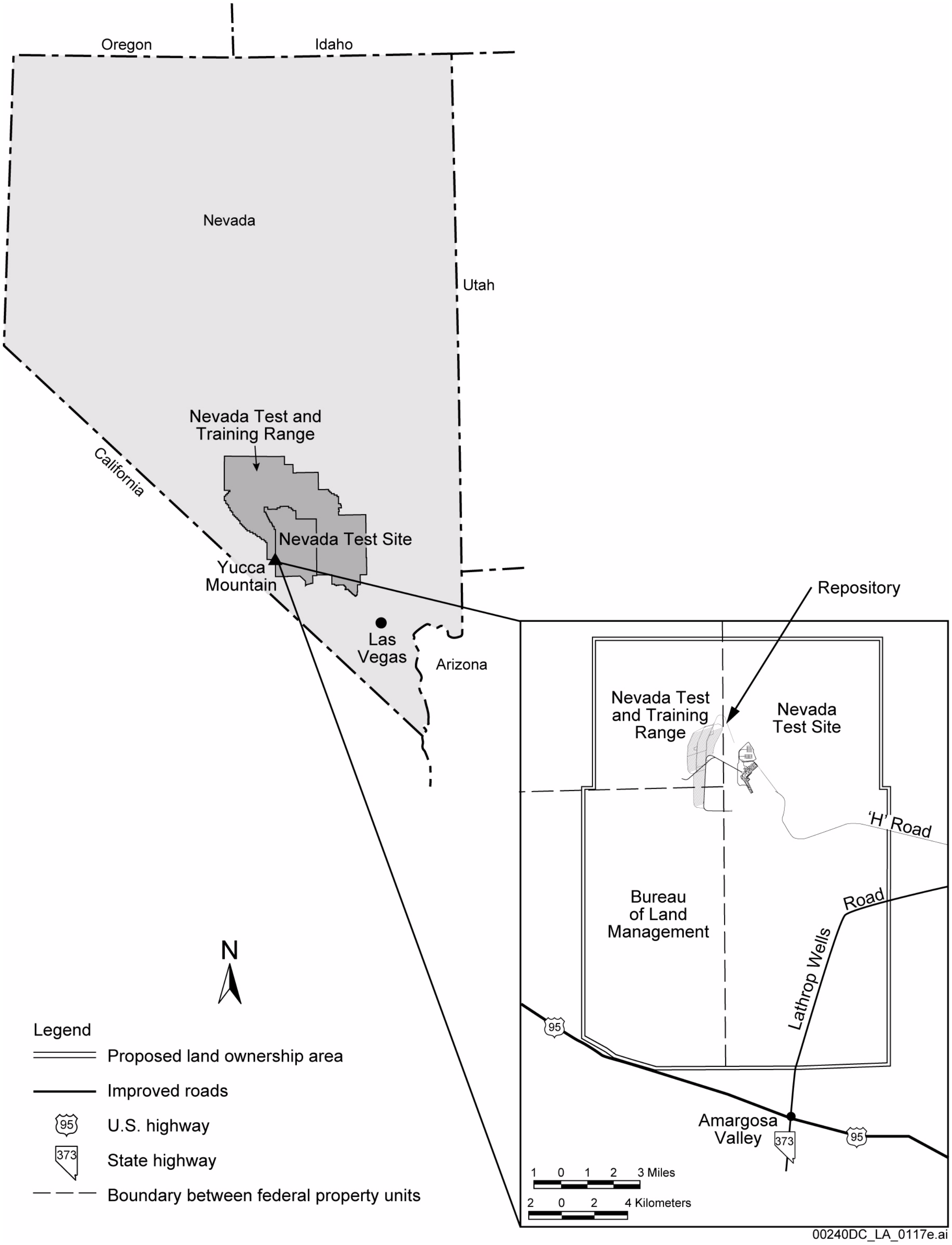


Figure 1-2. Federal Land Immediately Surrounding Yucca Mountain

Source: DOE 2002, Figure 1-6.

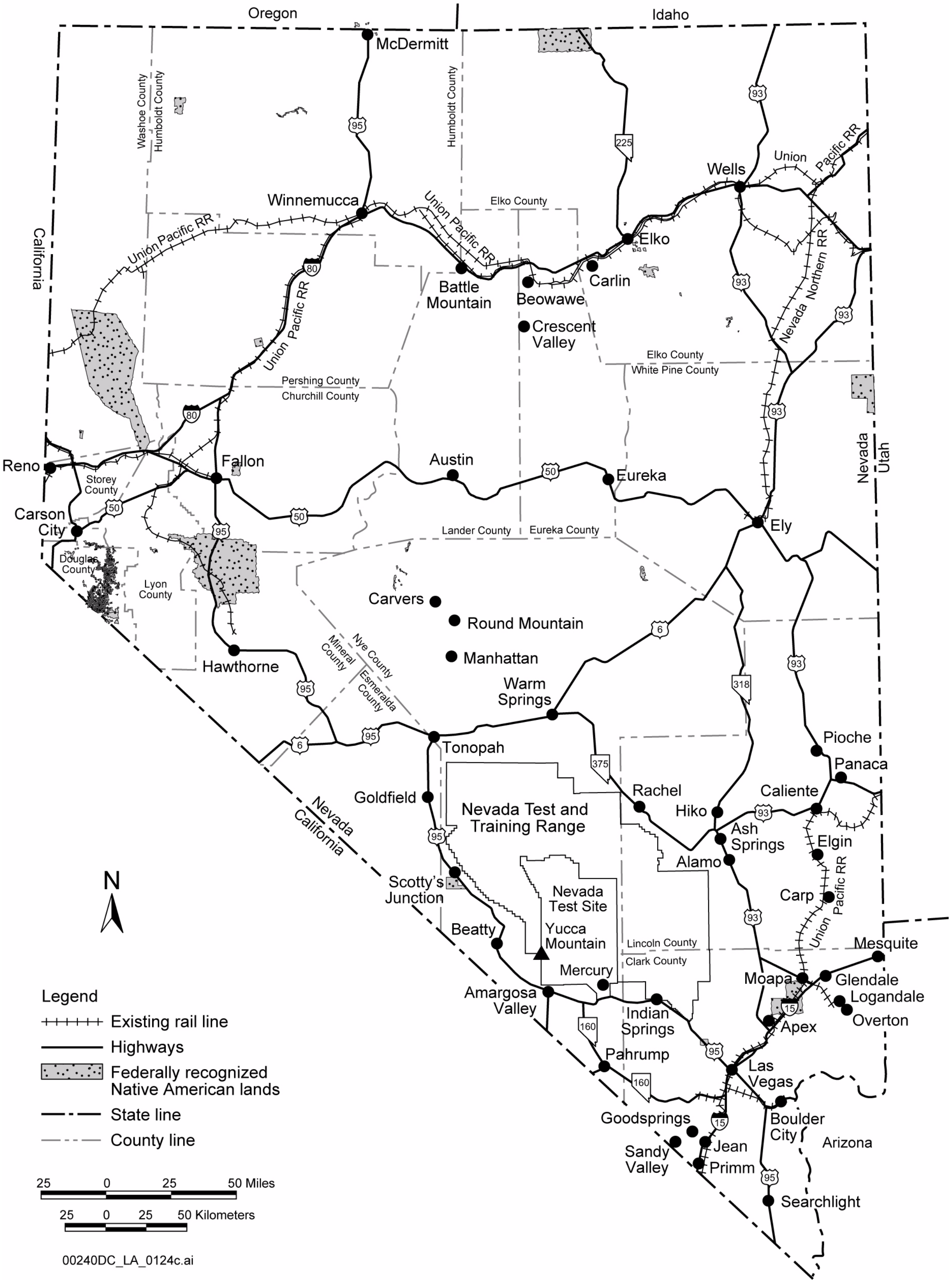


Figure 1-3. Counties of the State of Nevada

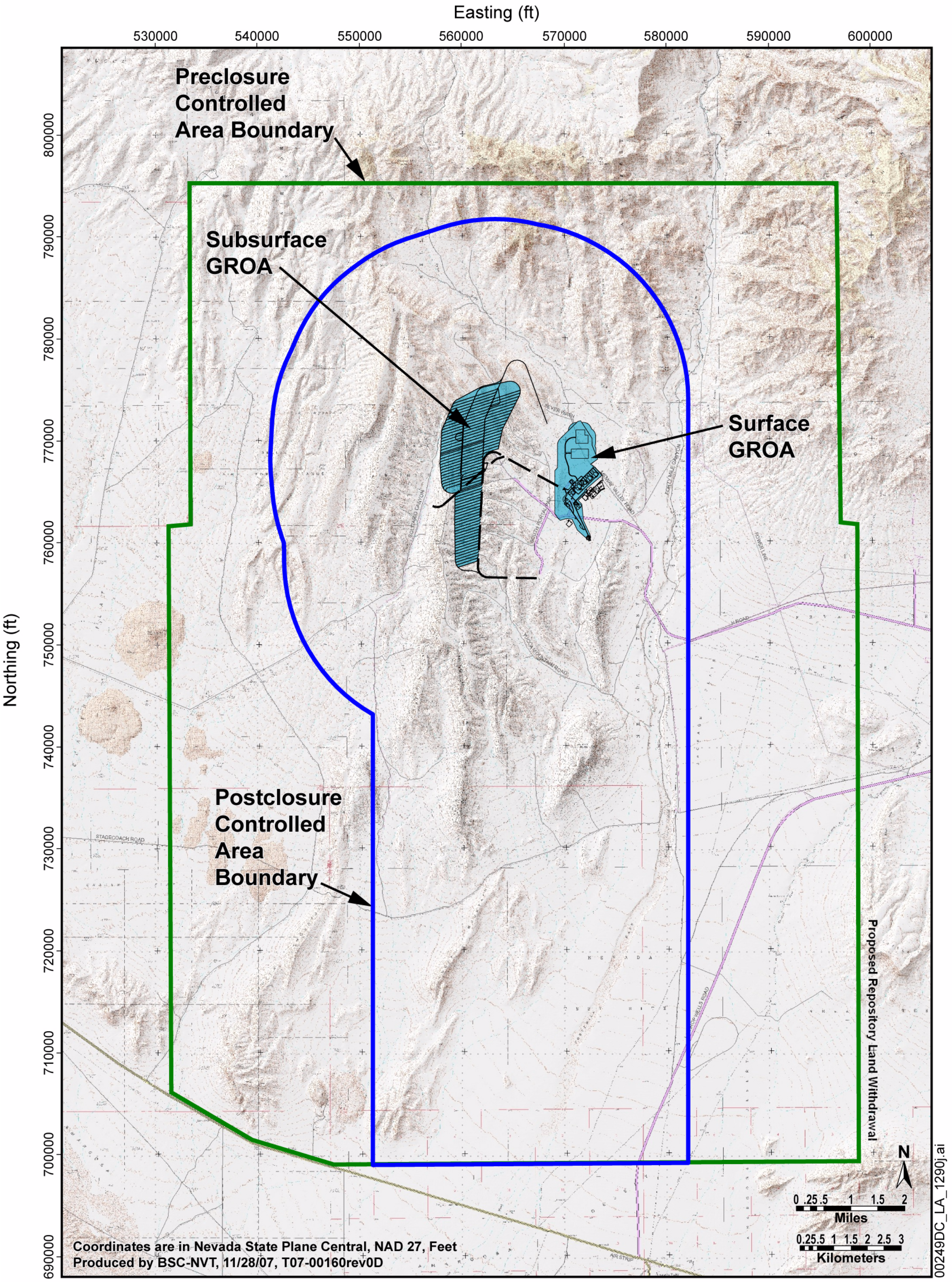
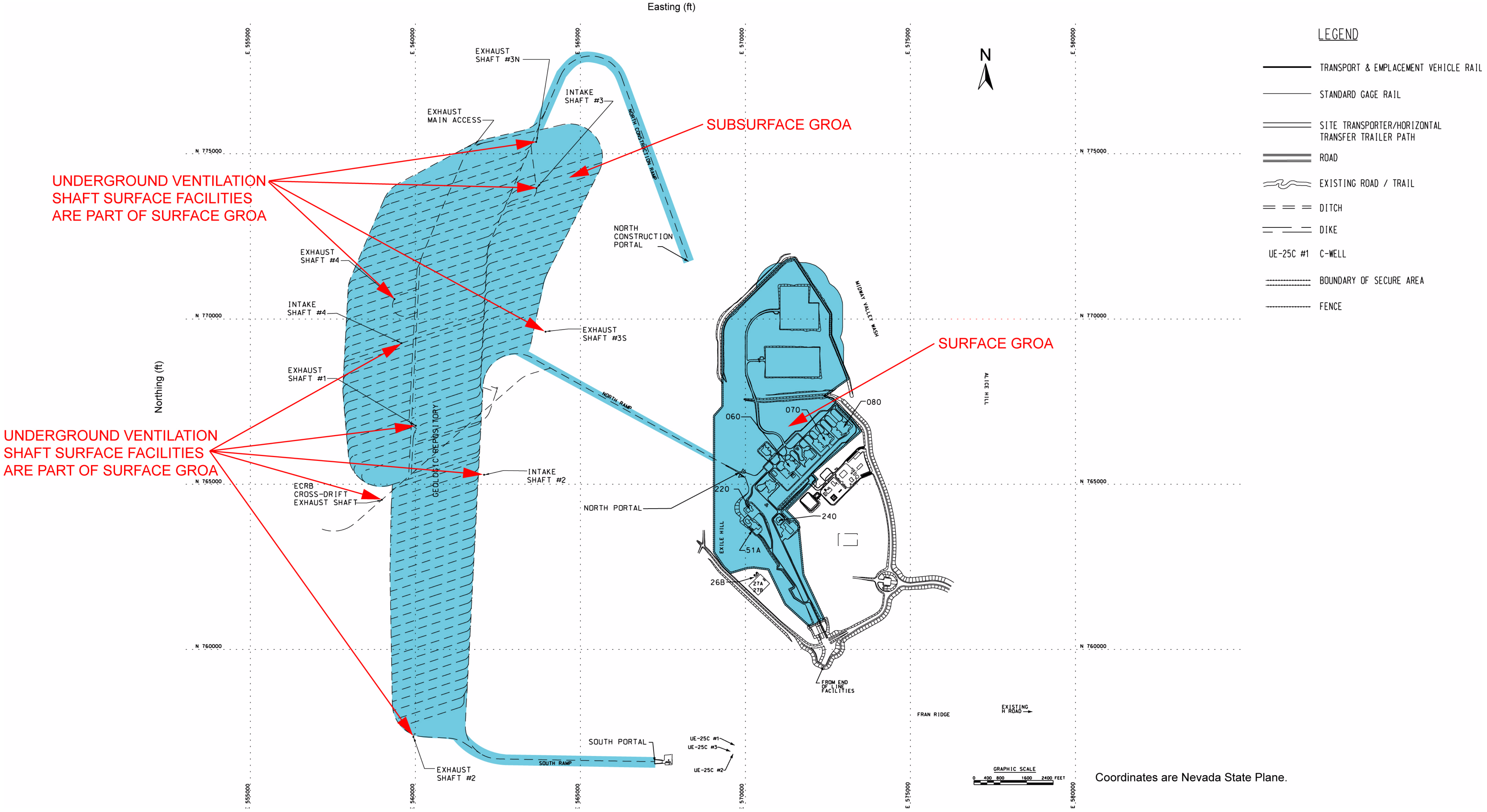


Figure 1-4. Site and Postclosure Controlled Area Boundaries



Coordinates are Nevada State Plane.

Figure 1-5. Geologic Repository Operations Area

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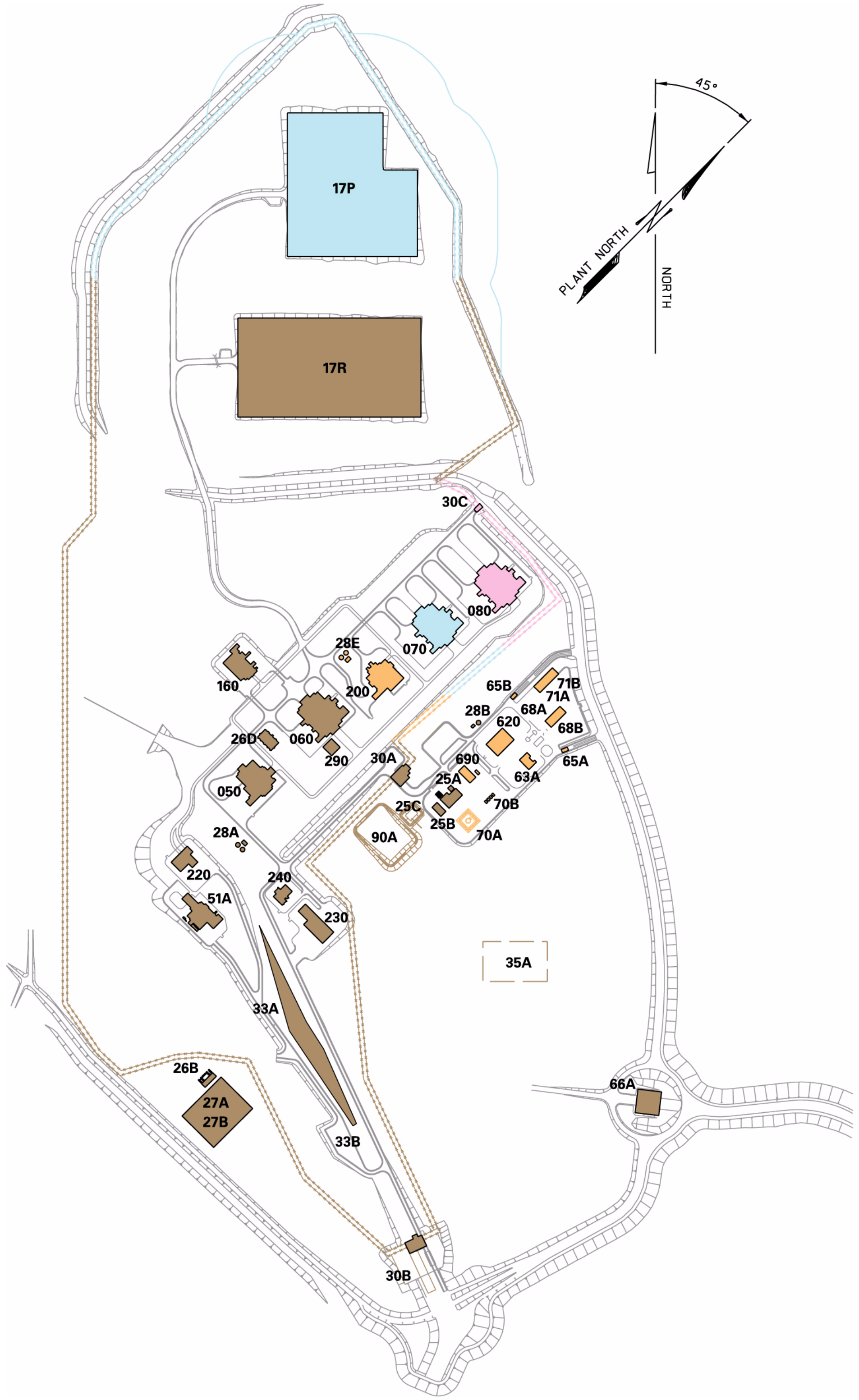

LEGEND

Initial Operating Capability

Phase 1

050	Wet Handling Facility	26D	Emergency Diesel Generator Facility
060	Canister Receipt and Closure Facility 1	27A	Switchyard (138kV)
51A	Initial Handling Facility	27B	13.8kV Switchgear Facility
17R	Aging Pad R	28A	Fire Water Facility
160	Low-Level Waste Facility	28B	Fire Water Facility
220	Heavy Equipment Maintenance Facility	30A	Central Security Station
230	Warehouse and Non-Nuclear Receipt Facility	30B	Cask Receipt Security Station
240	Central Control Center Facility	33A	Rail Car Buffer Area
25A	Utility Facility	33B	Truck Buffer Area
25B	Cooling Tower	35A	Septic Tank and Leach Field
25C	Evaporation Pond	66A	Helicopter Pad
26B	Standby Diesel Generator Facility	290	Aging Overpack Staging Facility
90A	Storm Water Retention Pond		

Full Operating Capability

Phase 2

200	Receipt Facility	68B	Materials/Yard Storage
28E	Fire Water Facility	690	Vehicle Maintenance and Motor Pool
620	Administration Facility	70A	Diesel Fuel Oil Storage
63A	Fire, Rescue and Medical Facility	70B	Fueling Stations
65A	Administration Security Station	71A	Craft Shops
65B	Administration Security Station	71B	Equipment/Yard Storage
68A	Warehouse/Central Receiving		

Phase 3

070	Canister Receipt and Closure Facility 2	17P	Aging Pad P

Phase 4

080	Canister Receipt and Closure Facility 3	30C	North Perimeter Security Station

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Figure 1-6. Surface Facilities Phased Construction

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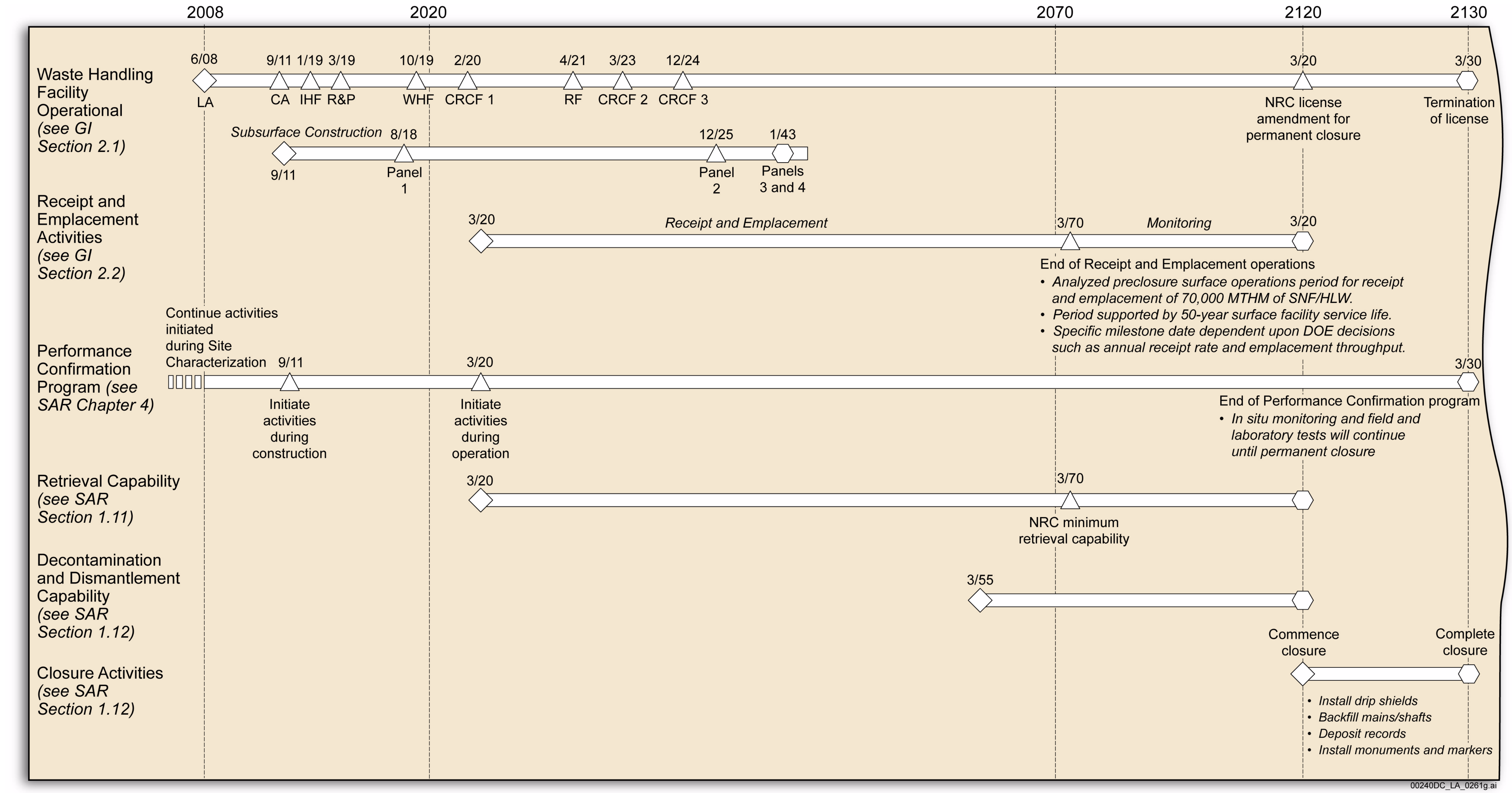

NOTE: CA = construction authorization; CRCF = Canister Receipt and Closure Facility; IHF = Initial Handling Facility; LA = license application; R&P = receive and possess; RF = Receipt Facility; WHF = Wet Handling Facility.

Figure 1-7. Repository Operations Summary Time Line

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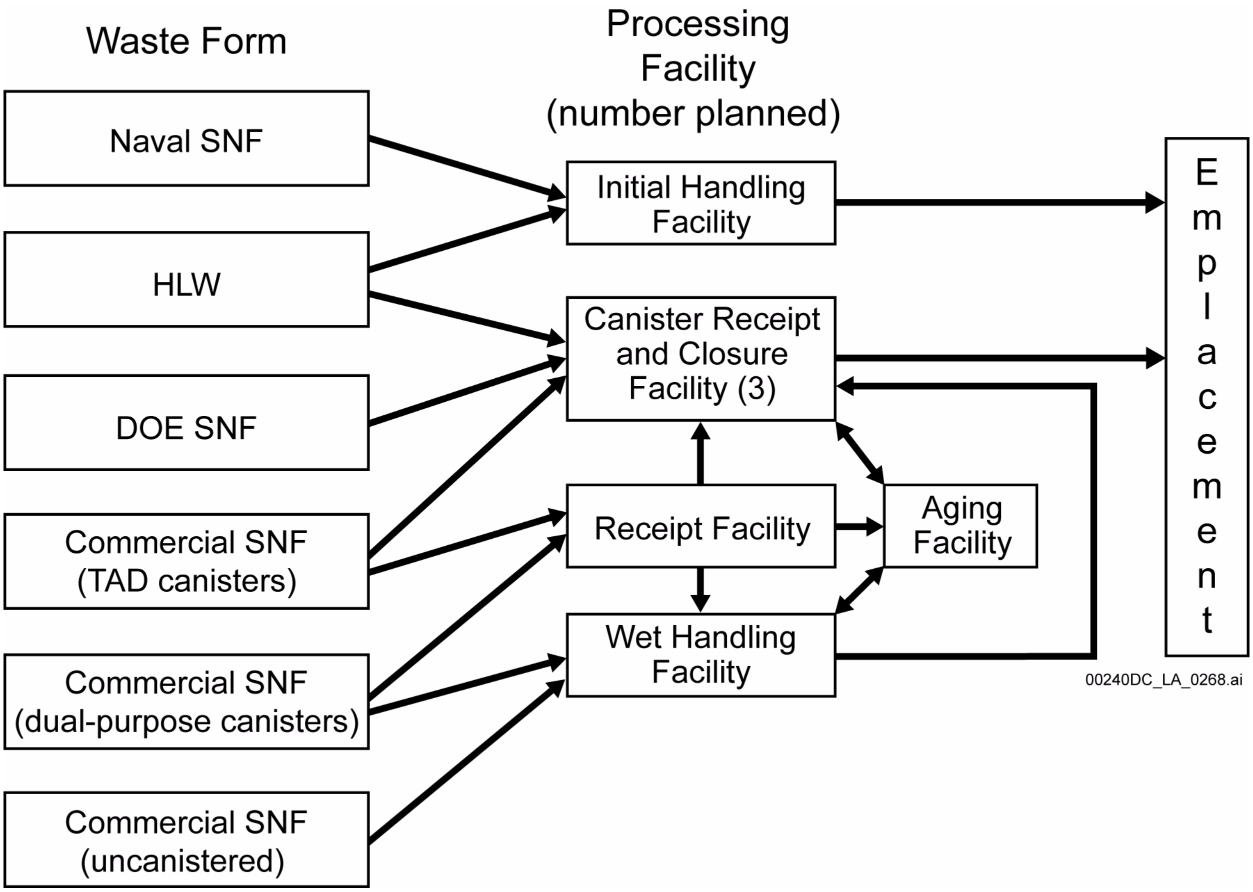

Figure 1-8. Waste Handling Process

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2. PROPOSED SCHEDULES FOR CONSTRUCTION, RECEIPT, AND EMPLACEMENT OF WASTE

This section provides information that addresses specific regulatory acceptance criteria in Section 1.2.3 of NUREG-1804. The information presented in this section also addresses the requirement contained in 10 CFR 63.21(b)(2). The following table lists the information provided in this section, the corresponding regulatory requirement, and applicable acceptance criteria from NUREG-1804.

GI Section	Information Category	10 CFR Part 63 Reference	NUREG-1804 Reference
2.1	Phased Construction Schedule	63.21(b)(2)	Section 1.2.3: Acceptance Criterion 1(1) Acceptance Criterion 1(3)
2.1.1	Initial Operating Capability	Not applicable	Section 1.2.3: Acceptance Criterion 1(1) Acceptance Criterion 1(3)
2.1.2	Full Operating Capability	Not applicable	Section 1.2.3: Acceptance Criterion 1(1) Acceptance Criterion 1(3)
2.2	Schedule for Waste Receipt and Emplacement	63.21(b)(2)	Section 1.2.3: Acceptance Criterion 1(2) Acceptance Criterion 1(3)

Consistent with 10 CFR 63.21(b)(2), the U.S. Department of Energy (DOE) has developed preliminary schedules for site preparation, construction, waste receipt, and routine emplacement operations. The schedules address the development of infrastructure inside and outside the geologic repository operations area (GROA), including site preparation and construction activities. To the extent they relate to radiological health and safety or preservation of the common defense and security, these activities will not commence inside the GROA until construction authorization is received from the U.S. Nuclear Regulatory Commission (NRC). Figure 2-1 presents an integrated summary of scheduled activities; supporting schedules are available for inspection.

The repository is designed to receive and emplace the types and quantities of radioactive waste described in Section 1.2.1. Upon completion of the repository site preparation and construction described in Section 2.1, and after an initial ramp-up period and attainment of near-steady-state operations, the DOE expects the repository to accommodate the following approximate annual waste receipt rates: 3,000 MTHM of commercial spent nuclear fuel (SNF) and commercial high-level radioactive waste (HLW), 763 canisters of defense HLW, up to 24 canisters of naval SNF, and 179 canisters of DOE SNF. Waste form quantities and properties are described in SAR Section 1.5.1. These types and quantities of waste are within the ranges of waste-handling operations used for categorization of internal hazard event sequences, as described in SAR Section 1.7.

Preliminary schedules have been developed that identify major steps for significant work elements supporting the design, construction, testing, and initial operation of the facilities to support the approximate rates of waste receipt. Construction of the GROA is not scheduled to be completed prior to initiating emplacement operations. A radiological access control and contamination boundary will be used to separate handling operations from ongoing construction activities in the GROA. A protected area boundary with physical barriers and isolation zones, and with radiological access controls provisions, will be used to separate handling operations from ongoing construction activities in the GROA. The emplacement drifts will also be developed as needed, rather than all drifts being completed prior to the start of operations. Surface handling facilities are not scheduled to be completed at the same time. However, consistent with 10 CFR 63.41(a)(1) and (2), those structures, systems, and components important to safety and necessary to permit initial receipt and emplacement capability of the waste forms will be installed and startup-tested prior to initial receipt of waste. As described in SAR Section 5.5, startup testing includes the surface, subsurface, and interconnecting structures, systems, and components important to safety, along with a sufficient number of subsurface emplacement drifts to support initial operations.

The primary assumptions used in developing the schedules for design, construction, testing, and initial operation are:

- No site preparation or construction activities related to radiological health and safety or preservation of the common defense and security will commence inside the GROA until after construction authorization is received from the NRC.

- Construction and operation of surface facilities is accomplished via a phased approach. Figure 2-2 illustrates the phases of surface facility construction.

- Underground panel construction is accomplished via a phased approach. Figure 2-3 illustrates the phased-panel layout of the underground facilities.

Section 2.1 presents information regarding the schedule for construction. Section 2.2 presents information on the schedule for waste receipt and emplacement. To accommodate the wide range of waste forms, shipping priorities, and shipping schedules and to enable efficient waste emplacement within limits imposed by thermal performance, waste package spacing, and specific waste package emplacement sequencing, waste emplacement operations may lag waste receipt activities.

2.1 PHASED CONSTRUCTION SCHEDULE

[NUREG-1804, Section 1.2.3: AC 1(1), (3)]

The repository will be constructed through four well-defined and manageable construction phases. The first phase (Phase 1) will result in those facilities comprising the initial operating capability as described in Section 2.1.1. The full operating capability is achieved by the subsequent three phases (Phases 2, 3, and 4) as described in Section 2.1.2. This construction is described in more detail in SAR Section 1.2.1 for surface facilities and in SAR Section 1.3.1 for subsurface facilities.

The objective of Phase 1 is to develop the capability to start operations, including development of those assets necessary to achieve a reasonable ramp-up of operations during the first several years of waste receipt. The objective of the subsequent operating phases is to develop full operating capability for receiving and emplacing the 70,000 MTHM currently authorized by law for the repository. A phased approach provides opportunities for implementing lessons learned for use on subsequently constructed facilities. Figure 2-2 illustrates the surface facility layout and construction phases. The following sections identify the construction phases of the facilities.

Detailed schedules for the development of facilities and infrastructure will be available for inspection by the NRC. The initial fabrication of empty waste packages is scheduled to begin in time to support initial emplacement operations.

2.1.1 Initial Operating Capability

[NUREG-1804, Section 1.2.3: AC 1(1), (3)]

The initial operating capability, Phase 1 construction, of the repository is provided by the Initial Handling Facility, the first Canister Receipt and Closure Facility (Canister Receipt and Closure Facility 1), the first portion of the Aging Facility, the Wet Handling Facility, and components of subsurface Panel 1. These facilities and their support facilities and systems include all necessary functional capabilities to receive, package, and emplace a limited throughput of canistered SNF and HLW and individual commercial SNF assemblies. Physical protection, material control and accounting, and emergency planning programs will be in place prior to start of initial operations.

2.1.1.1 Infrastructure

The site contains existing infrastructure that supports the existing facilities. This infrastructure includes roads, electrical power, water, sewer, and communications. The existing infrastructure will be modified as part of and to support site preparation and construction activities, as well as the operation of the repository; however, insofar as these modifications will occur inside the GROA and relate to radiological health and safety or preservation of the common defense and security, they will not commence prior to receiving construction authorization from the NRC. Infrastructure that will be developed to support repository operations is identified with each phase, as it is to be developed, and is included in the construction schedule.

Some of the infrastructure to be developed outside the GROA will include:

- Rail line
- Communication system improvements
- Electric transmission lines.

Other infrastructure to be developed, some of which will be located inside the GROA, will include the following. To support phased construction and operation of the full operating capability, road construction will continue after initial operating capability is achieved.

- Construction fire, rescue, and medical facilities, workforce shops, offices, warehouses, and laydown yards near the North Portal, South Portal, and new North Construction Portal

- Qualified borrow pits and concrete batch plants

- Raw materials and engineered fill stockpiles
- Raw water supplies and delivery system
- Waste water collection and control system
- Electrical transmission line and switchyard for construction
- Exploratory Studies Facility muck pile and undocumented fill, relocated away from the North Portal area
- Removal of existing North Portal structures and facilities
- Access road from off site
- Rail line from off site.

This infrastructure will be part of and support site preparation and construction activities; however, no such activities that relate to radiological health and safety or preservation of the common defense and security will commence inside the GROA prior to receiving construction authorization from the NRC.

2.1.1.2 Initial Handling Facility

The Initial Handling Facility is a transfer facility that is designed to receive, by rail or truck shipment, only naval SNF canisters or DOE HLW canisters. The Initial Handling Facility is designed to transfer canisters into waste packages and load the sealed waste packages into the shielded transport and emplacement vehicle (TEV) in preparation for emplacement.

2.1.1.3 Canister Receipt and Closure Facility 1, Panel 1, Initial Aging

Canister Receipt and Closure Facility 1 includes the necessary functional capabilities to receive (by truck or rail), package, and emplace transportation, aging, and disposal (TAD) canisters, HLW canisters, and DOE SNF canisters. Handling features are included to transfer TAD canisters into overpacks for aging. Canister Receipt and Closure Facility 1 also receives loaded aging overpacks and transfers their TAD canisters into waste packages. Canister Receipt and Closure Facility 1 and subsequent canister receipt and closure facilities handle no uncanistered SNF. For TAD canisters in aging overpacks, the above-surface Aging Facility provides space for aging waste for the initial operating capability. Sealed waste packages are loaded into the shielded TEV in preparation for emplacement.

The subsurface facilities are scheduled for phased development by panels. Figure 2-3 illustrates the phased-panel layout of the underground facilities. A small number of drifts in Panel 1, including those assigned to performance confirmation testing, are scheduled for completion (Figure 2-1) to support the initial operating capability of the surface facilities (Figure 2-2). Waste packages will be moved from the waste handling facilities to the emplacement drifts using the crane-based, shielded TEV.

2.1.1.4 Wet Handling Facility

The Wet Handling Facility is designed to receive, by rail or truck shipment, only commercial SNF, either uncanistered or in dual-purpose canisters. Dual-purpose canisters may also be received from the Aging Facility, in overpacks, on the site transporter. The Wet Handling Facility is designed to repackage uncanistered SNF into TAD canisters, or from the dual-purpose canisters into TAD canisters while submerged in a wet handling pool. Sealed TAD canisters are transported in aging overpacks either to the Aging Facility or to a Canister Receipt and Closure Facility where the TAD canisters are loaded into waste packages.

2.1.1.5 Additional Facilities Supporting Initial Operation

The following additional facilities are scheduled for completion to support the repository initial operating capability as described above:

- Surface nuclear handling facilities:

    - Initial capacity of the Aging Facility (Aging Pad 17R)
    - Aging Overpack Staging Facility.

- Balance of plant surface facilities that provide infrastructure services:

    - Low-Level Waste Facility
    - Cask Receipt Security Station
    - Utilities Facility and cooling tower
    - Evaporation pond
    - Emergency Diesel Generator Facility and associated buried fuel oil tanks
    - Standby Diesel Generator Facility and associated buried fuel oil tanks
    - Switchyard and switchgear facility
    - Central Security Station
    - Railcar and truck buffer areas
    - Fire water facilities (two)
    - Helicopter pad
    - Storm water retention pond
    - Septic tank and leach field
    - Heavy Equipment Maintenance Facility
    - Central Control Center Facility
    - Warehouse and Non-Nuclear Receipt Facility.

- Subsurface emplacement drifts 1 to 3 in Panel 1 (Figure 2-3), including one or more drifts that will be monitored under the Performance Confirmation Program for host-rock near-field coupled processes, and one observation drift. Ventilation for the subsurface is developed in a phased manner to support emplacement operations.

To the extent any of the site preparation or construction activities involving these facilities relate to radiological health and safety or preservation of the common defense and security, they will not commence inside the GROA until construction authorization is received from the NRC.

To prepare for the submission of an updated license application to receive and possess SNF and HLW and to prepare for operations, additional required activities are anticipated during the initial construction period. These activities include updating of additional geologic, geophysical, geochemical, hydrologic, meteorologic, materials, design, and other data obtained during construction; verifying conformance of construction of structure, system, or component with the design; and results of any research programs carried out to confirm the adequacy of designs, conceptual models, parameter values, and estimates of performance of the geologic repository. Plans and procedures will be developed and implemented for personnel training, startup activities and testing, conduct of normal activities and establishment of baseline parameters for repository performance confirmation. The updated license application will provide the information required by 10 CFR 63.24(b), including updated waste receipt and emplacement schedules.

2.1.2 Full Operating Capability

[NUREG-1804, Section 1.2.3: AC 1(1), (3)]

2.1.2.1 Receipt Facility

To increase throughput capabilities, the full operating capability includes additional high-throughput handling facilities similar to those developed for the initial operating capability. The three handling facilities operable from Phase 1 are complemented in Phase 2 by a Receipt Facility that is designed to receive rail casks containing commercial waste canisters, to prepare the casks for transfer, and to transfer canisters to an aging overpack for movement to other facilities. Also within the Receipt Facility, unloaded transportation casks and railcar conveyances are prepared for return to transportation service. Additional balance of plant facilities are included in Phase 2 to support operations in this phase. Increased numbers of waste packages will be procured. The following facilities are scheduled for completion in Phase 2 to support the first increment of full operating capability:

- Surface handling facilities:

    – Receipt Facility.

- Balance of plant surface facilities that provide infrastructure services:

    – Warehouse, central receiving, and yard storage areas
    – Fire water facility (third of three)
    – Fire, rescue, and medical facility
    – Administration Facility
    – Expanded diesel fuel oil storage
    – Administration security stations
    – Craft shops, vehicle maintenance, and fueling stations
    – Visitors Center (to be sited later).

- Subsurface: Remainder of Panel 1 and Panel 2. Construction of Panels 3 and 4 will be ongoing throughout this and subsequent phases.

2.1.2.2 Canister Receipt and Closure Facilities 2 and 3, Additional Aging

The following additional handling facilities are scheduled for completion in Phase 3 to support the second increment of full operating capability:

- Canister Receipt and Closure Facility 2
- Final capacity of the Aging Facility (Aging Pad 17P) to support operations.

The following additional handling facilities are scheduled for completion in Phase 4 to support the final increment of full operating capability:

- Canister Receipt and Closure Facility 3.

Additionally, the North Perimeter Security Station is added in Phase 4 for additional control of access to the GROA from the north.

2.2 SCHEDULE FOR WASTE RECEIPT AND EMPLACEMENT

[NUREG-1804, Section 1.2.3: AC 1(2), (3)]

Figure 2-1 presents an integrated summary of scheduled activities; supporting schedules are available for inspection by the NRC. Receipt and emplacement operations are projected to span 50 years which is a period covered by the preclosure safety analysis. The total period covered by the preclosure safety analysis is 100 years which includes a 50-year period, after receipt and emplacement, that considers the impact of external events on the subsurface and internal events such as loss of subsurface cooling. Throughout emplacement operations, development of emplacement drifts is scheduled to support receipt rates. The surface facility handling throughput of each facility during the preclosure period is shown in SAR Table 1.2.1-1.

Specific emplacement schedules depend upon the logistics related to specific waste types and characteristics, the need for aging, the need to blend waste forms within waste packages to meet waste package thermal limits, and the need to support specific emplacement drift waste package patterns consistent with the analyzed thermal basis.

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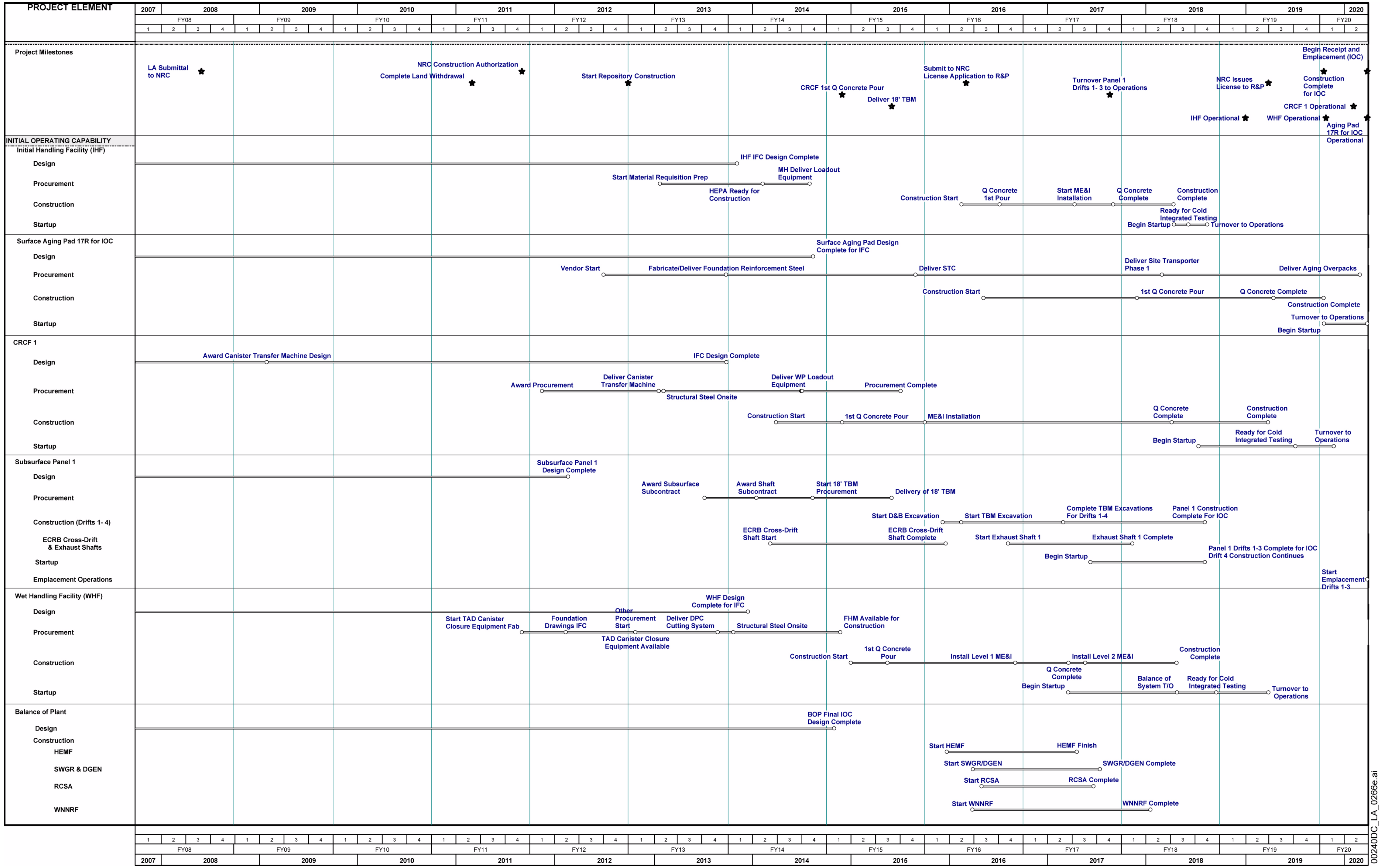

NOTE: CRCF = Canister Receipt and Closure Facility; DPC = dual-purpose canister; HEPA= high-efficiency particulate air; HEMF = Heavy Equipment Maintenance Facility; IFC = issue for construction; IHF = Initial Handling Facility; LA = license application; ME&I = mechanical, electrical, and instrumentation; MH = mechanical handling; R&P = receive and possess; RCSA = railcar staging area; STC = shielded transfer cask; SWGR/DGEN = switchgear building and diesel generator; TBM = tunnel boring machine; WHF = Wet Handling Facility; WNNRF = Warehouse and Non-Nuclear Receipt Facility; WP = waste package.

Figure 2-1. High-Level Project Schedule (Sheet 1 of 3)

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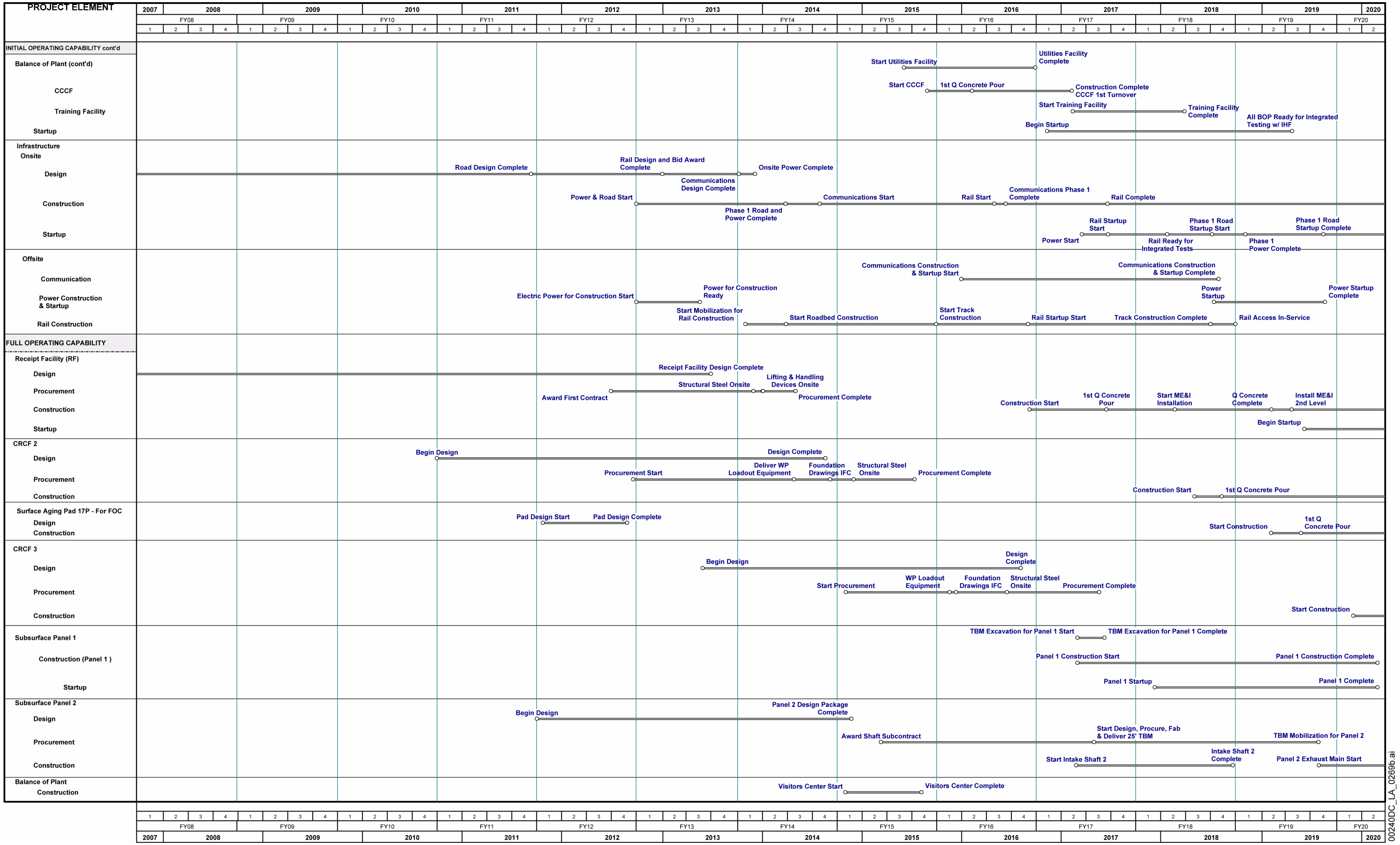

NOTE: CCCF = Central Control Center Facility; IFC = issue for construction; IHF = Initial Handling Facility; ME&I = mechanical, electrical, and instrumentation; RF = Receipt Facility; TBM = tunnel boring machine; WP= waste package.

Figure 2-1. High-Level Project Schedule (Sheet 2 of 3)

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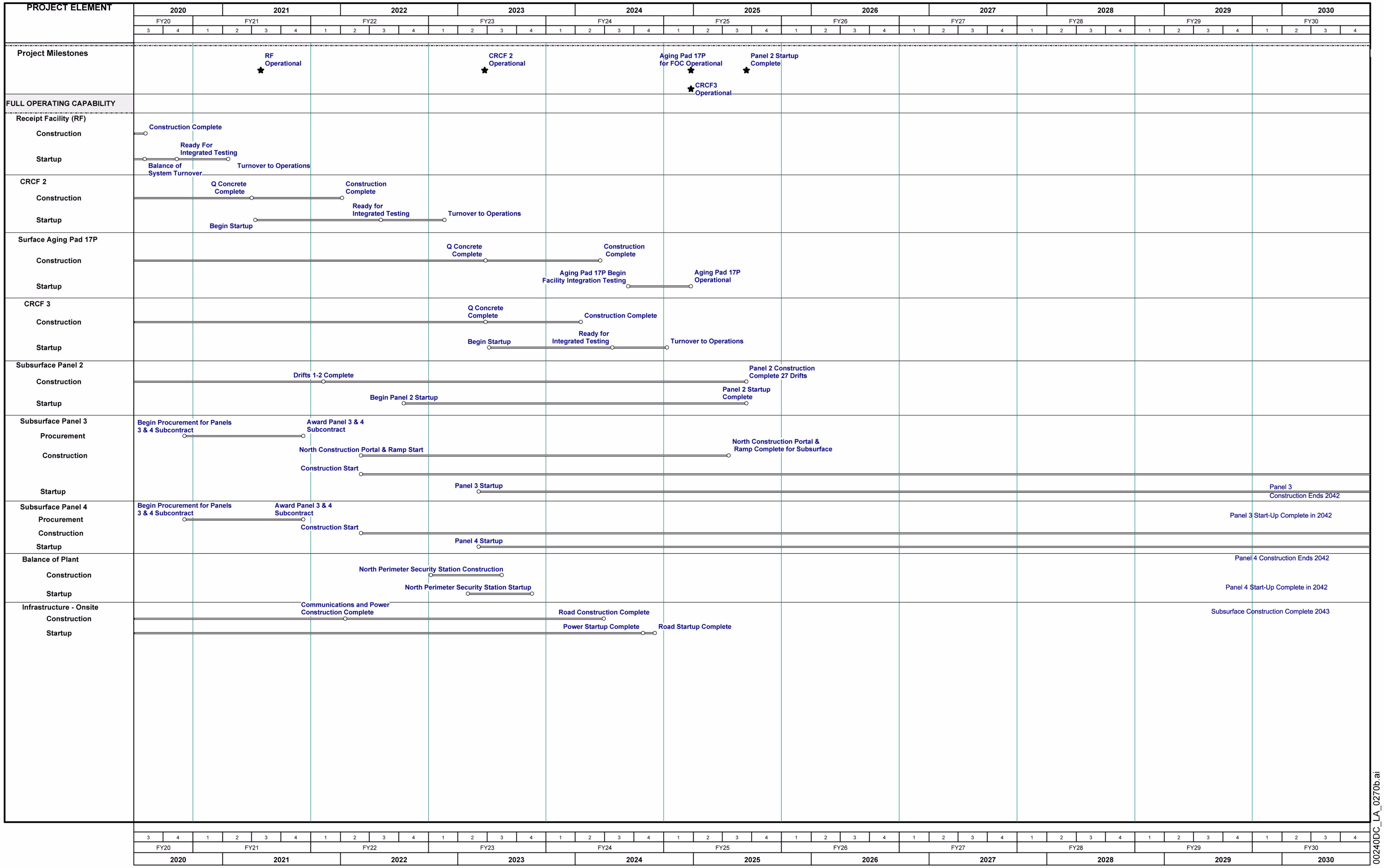

NOTE: CRCF = Canister Receipt and Closure Facility; RF = Receipt Facility.

Figure 2-1. High-Level Project Schedule (Sheet 3 of 3)

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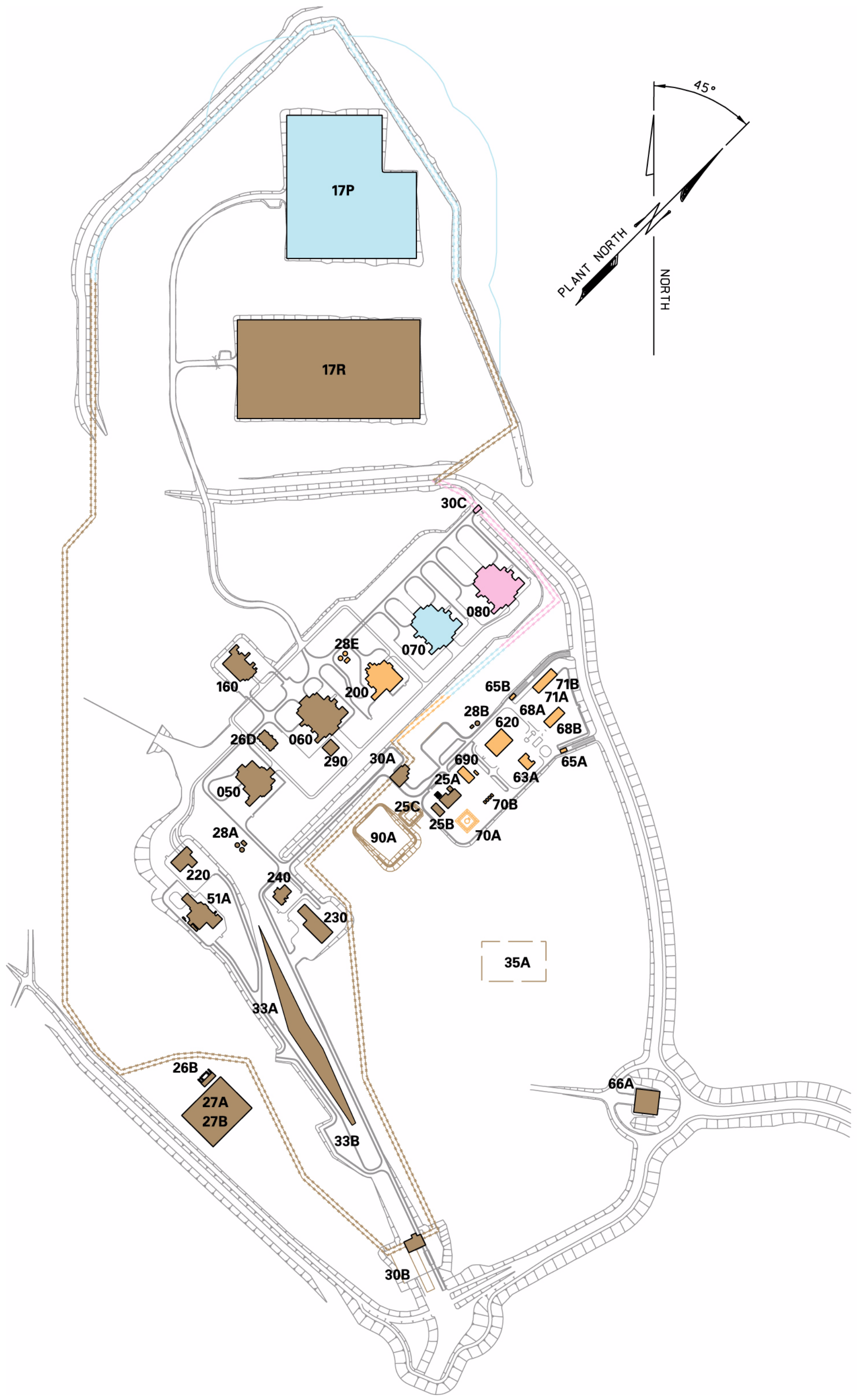

LEGEND			
Initial Operating Capability			
Phase 1			
050	Wet Handling Facility	26D	Emergency Diesel Generator Facility
060	Canister Receipt and Closure Facility 1	27A	Switchyard (138kV)
51A	Initial Handling Facility	27B	13.8kV Switchgear Facility
17R	Aging Pad R	28A	Fire Water Facility
160	Low-Level Waste Facility	28B	Fire Water Facility
220	Heavy Equipment Maintenance Facility	30A	Central Security Station
230	Warehouse and Non-Nuclear Receipt Facility	30B	Cask Receipt Security Station
240	Central Control Center Facility	33A	Rail Car Buffer Area
25A	Utility Facility	33B	Truck Buffer Area
25B	Cooling Tower	35A	Septic Tank and Leach Field
25C	Evaporation Pond	66A	Helicopter Pad
26B	Standby Diesel Generator Facility	290	Aging Overpack Staging Facility
90A	Storm Water Retention Pond		
Full Operating Capability			
Phase 2			
200	Receipt Facility	68B	Materials/Yard Storage
28E	Fire Water Facility	690	Vehicle Maintenance and Motor Pool
620	Administration Facility	70A	Diesel Fuel Oil Storage
63A	Fire, Rescue and Medical Facility	70B	Fueling Stations
65A	Administration Security Station	71A	Craft Shops
65B	Administration Security Station	71B	Equipment/Yard Storage
68A	Warehouse/Central Receiving		
Phase 3			
070	Canister Receipt and Closure Facility 2	17P	Aging Pad P
Phase 4			
080	Canister Receipt and Closure Facility 3	30C	North Perimeter Security Station

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Figure 2-2. Surface Facilities—Phased Construction

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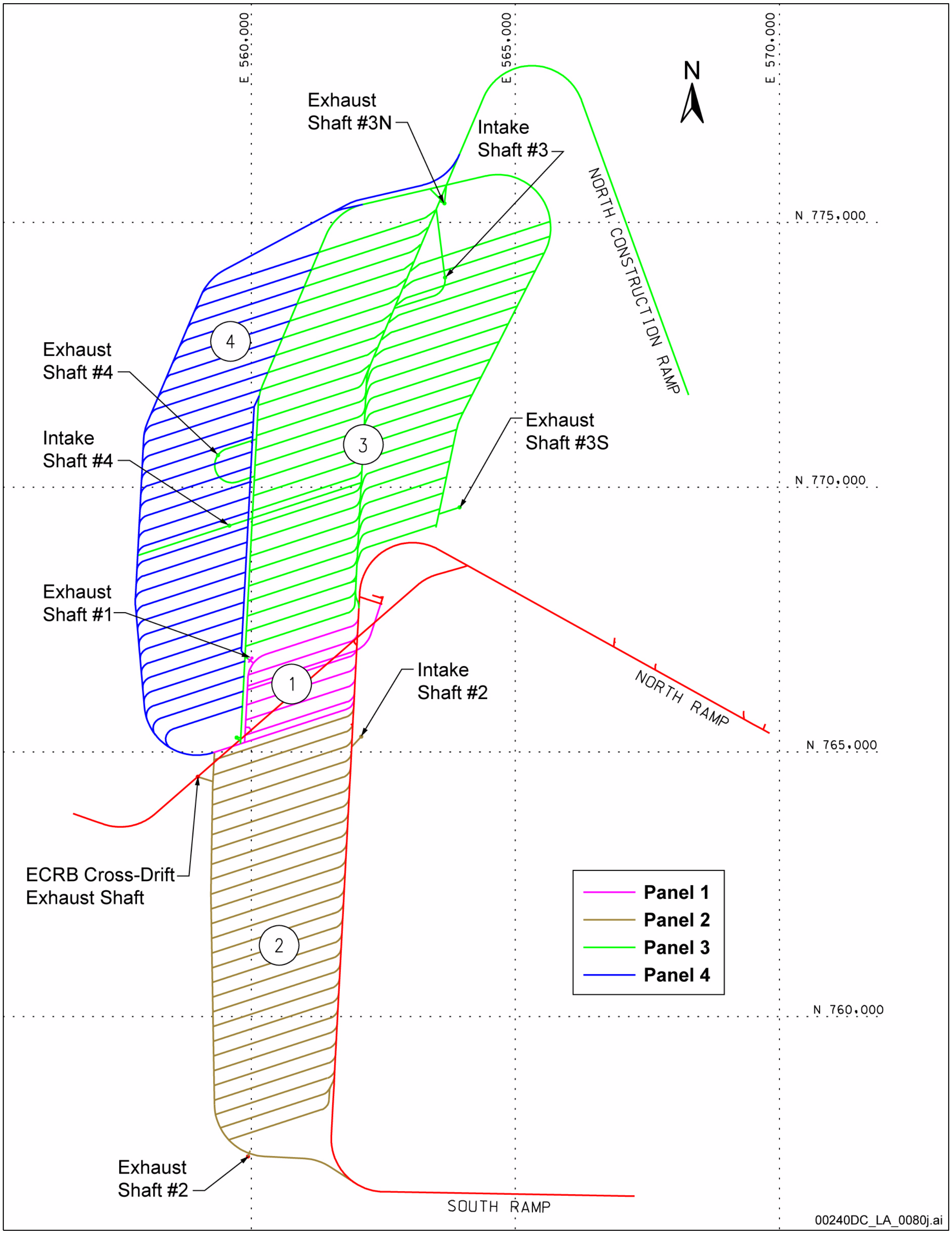

Figure 2-3. Underground Facilities—Phased Panel Layout

NOTE: ECRB = Enhanced Characterization of the Repository Block.

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3. PHYSICAL PROTECTION PLAN

This section of the license application addresses the requirements of 10 CFR 63.21(b)(3) by providing a description of the detailed security measures for physical protection of spent nuclear fuel (SNF) and high-level radioactive waste (HLW) at the Yucca Mountain repository. The general description provided in this section is suitable for public disclosure.

A Physical Protection Plan, compliant with applicable portions of 10 CFR Part 73, will be submitted to the U.S. Nuclear Regulatory Commission (NRC) no later than 180 days after the NRC issues a construction authorization.

The U.S. Department of Energy (DOE) will withhold the Physical Protection Plan from public disclosure, in accordance with Executive Order 12958 (60 FR 19825), and applicable exemptions set forth in the Freedom of Information Act (5 U.S.C. 552). The plan also will be protected from public disclosure under the NRC regulations set forth in 10 CFR 73.21(b).

Effective implementation of the Physical Protection Plan is one of the elements that provides assurance that activities involving waste do not present an unreasonable risk to the health and safety of the public. As required by 10 CFR 73.51(b)(3), the Physical Protection Plan will describe the physical protection system for the geologic repository operations area (GROA), which will be designed to protect against a loss of control of the facilities that could cause radiation exposures exceeding the doses described in 10 CFR 72.106.

Protected area operations, where waste handling occurs, will be separated from construction activities by physical barriers and isolation zones (as defined in 10 CFR 73.2) so that construction activities can proceed without impacting operations. The security requirements for the operating areas of the GROA inside the protected area where nuclear material is present will be different from the security requirements for areas within the GROA outside the protected area where construction activities are occurring. Those requirements and the resulting levels of protection will be described in the Physical Protection Plan.

The plan will be developed and maintained to provide a description of the:

- Isolation zones, as defined in 10 CFR 73.2
- GROA, including the nature and the amount of wastes, as well as a plan implementation schedule that meets the performance objectives of 10 CFR 73.51
- Security organization, physical protection systems, and other means that are used to protect the GROA against a loss of control that could cause radiation exposures exceeding the doses described in 10 CFR 72.106
- Physical barrier, access control, detection, surveillance, alarm, and communication subsystems that protect against unauthorized penetration and unauthorized removal, theft, or diversion of nuclear material and against radiological sabotage

- Equipment test and maintenance activities that provide confidence in the effectiveness, availability, reliability, maintainability, and integrity of security equipment and subsystems

- Safeguards Contingency Plan for responding to unauthorized penetrations of or activities within the protected area, identifying predetermined responses to safeguards contingency events, and the process for reporting safeguards events to the NRC, consistent with the requirements of 10 CFR 73, Appendix G.

The attributes of the Physical Protection Plan described in this section provide an overview of how the general performance requirements, performance capabilities, and specific requirements in the regulations will be developed and implemented and form the basis for meeting the requirements of 10 CFR 63.21(b)(3) and 10 CFR 73.51. This section provides information that addresses specific regulatory acceptance criteria in Section 1.3.3 of NUREG-1804. The information also addresses applicable requirements contained in 10 CFR Part 63, 10 CFR Part 72, and 10 CFR Part 73. The following table lists the information provided in this section, the corresponding regulatory requirements, and the applicable acceptance criteria from NUREG-1804.

GI Section	Information Category	10 CFR Reference	NUREG-1804 Reference
3.1	Description and Schedule for Implementation	63.21(b)(3) 73.51 73.51(c)	Section 1.3.3: Acceptance Criterion 1
3.2	General Performance Objectives	63.21(b)(3) 73.51(b)(1) 73.51(b)(2)	Section 1.3.3: Acceptance Criterion 2
3.3	Protection Goal and Strategy	63.21(b)(3) 72.106 73.51(b)(3)	Section 1.3.3: Acceptance Criterion 3
3.4	Security Organization	63.21(b)(3) 73.51(d)(5) 73.51(d)(12) 73, Appendix B Part 1046 Part 1047	Section 1.3.3: Acceptance Criterion 4
3.5	Physical Barrier Subsystems	63.21(b)(3) 73.2 73.51(d)(1) 73.51(d)(2)	Section 1.3.3: Acceptance Criterion 5
3.6	Access Control Subsystems and Procedures	63.21(b)(3) 73.51(d)(7) 73.51(d)(9) 73.51(d)(13)	Section 1.3.3: Acceptance Criterion 6
3.7	Detection, Surveillance, Alarm Subsystems, and Procedures	63.21(b)(3) 73.51(d)(3) 73.51(d)(4) 73.51(d)(11)	Section 1.3.3: Acceptance Criterion 7

GI Section	Information Category	10 CFR Reference	NUREG-1804 Reference
3.8	Communication Subsystem	63.21(b)(3) 73.51(d)(8)	Section 1.3.3: Acceptance Criterion 8
3.9	Equipment Operability and Compensatory Measures	63.21(b)(3) 73.51(d)(11)	Section 1.3.3: Acceptance Criterion 9
3.10	Safeguards Contingency Plan	63.21(b)(3) 73.51(d)(6) 73.51(d)(10) 73, Appendix B 73, Appendix C	Section 1.3.3: Acceptance Criterion 10
3.11	Reporting of Safeguards Events	63.21(b)(3) 73, Appendix G	Section 1.3.3: Acceptance Criterion 11
3.12	Records Retention	73.51(d)(13)	Section 1.3.3: Acceptance Criterion 4(5)

3.1 DESCRIPTION AND SCHEDULE FOR IMPLEMENTATION
[NUREG-1804, Section 1.3.3: AC 1]

The Physical Protection Plan will describe the GROA and will be updated as the protected area within the GROA changes to accommodate phased operations of the waste handling facilities. It will specify the locations of physical protection systems, subsystems, and major components of the GROA facilities. This information will be included in the description of the layout of the protected area and the locations of buildings. The locations of security posts, access control points, and detection alarm systems will also be identified. Maps and plot plans will be provided. The plan will identify tests, inspections, audits, and other means to be used to demonstrate compliance with 10 CFR 73.51. The plan will include a schedule for implementation of physical protection. The security program will be operational and performance-tested prior to receipt of SNF and HLW. Consistent with 10 CFR 73.51(c), copies of the Physical Protection Plan and changes thereto will be treated as records for 3 years or until termination of the license.

3.2 GENERAL PERFORMANCE OBJECTIVES
[NUREG-1804, Section 1.3.3: AC 2]

The Physical Protection Plan will meet the general performance objectives and requirements of 10 CFR 73.51(b)(1) by establishing, implementing, and maintaining a physical protection system that provides assurance that activities involving SNF and HLW do not present an unreasonable risk to the health and safety of the public. The plan will describe those portions of the physical protection system for which redundant and diverse subsystems and components are necessary in order to meet the requirements of 10 CFR 73.51(b)(2). The physical protection system will be designed and performance-tested to provide assurance that the system functions as intended. The plan will describe the design and how the system is tested and maintained to ensure its continued effectiveness, availability, reliability, and maintainability.

3.3 PROTECTION GOAL AND STRATEGY

[NUREG-1804, Section 1.3.3: AC 3]

Consistent with 10 CFR 73.51(b)(3), implementation of the Physical Protection Plan will address protection of the protected area of the GROA against a loss of control that could cause radiation exposures exceeding the dose described in 10 CFR 72.106. To ensure that this protection goal is met, the Physical Protection Plan will identify a security force; physical barriers; access controls; intrusion detection, assessment, and surveillance systems; communication equipment; and contingency and response plans and procedures. The plan will describe the strategy for denying unauthorized access. The DOE will maintain and update the Physical Protection Plan to reflect changes necessary to ensure its continued effectiveness.

3.4 SECURITY ORGANIZATION

[NUREG-1804, Section 1.3.3: AC 4]

The Physical Protection Plan will describe how the security organization manages, controls, and implements the physical protection system while continually assessing and maintaining its effectiveness. The plan will describe the security organization that will be established and maintained. This security organization will operate in accordance with written procedures and written agreements, and the plan will indicate whether the security force is composed of federal employees or a contract security force. If a contract security force is selected, the DOE will establish written agreements that will govern how the contract security force meets the requirements of 10 CFR 73.51(d)(5) and 10 CFR 73, Appendix B. The security force will be subject to a fitness-for-duty program as applicable. The security organization will be in place prior to receipt of waste.

The plan will define site security responsibilities and detail the reporting lines from a Site Protection Manager down to those federal or contract employees who are assigned the responsibility for the direct supervision of physical security activities and security personnel. The security organization will provide sufficient personnel for each shift to provide for monitoring of detection systems and the conduct of surveillance, assessments, access control, and communications to ensure adequate response.

Consistent with 10 CFR 73.51(d)(12), assessments of the Physical Protection Plan will be performed at least once every 24 months by individuals independent of both physical protection management and personnel who have direct responsibility for implementation. The qualifications for individuals performing the assessments will be described in the Physical Protection Plan and its implementing procedures. These assessments will verify the effectiveness of the Physical Protection Plan and the liaison with and the training of the designated offsite response force and any local law enforcement agency.

The Physical Protection Plan will describe the process for selecting, qualifying, training, and equipping members of the security organization to enable them to perform their security duties as identified in the Physical Protection Plan, the Safeguards Contingency Plan, and the Training and Qualification Plan, in accordance with 10 CFR 73.51(d)(5). The security force will operate under DOE authority to carry firearms and make limited arrests consistent with 10 CFR Part 1046, Physical Protection of Security Interests, and 10 CFR Part 1047, Limited Arrest Authority and Use of Force by Protective Force Officers. Security force suitability and qualifications include physical suitability and requirements for education, reasoning skills, and knowledge of and ability to perform the security-related tasks identified in the Physical Protection Plan and Safeguards Contingency Plan. As described in the plans, each member of the security organization will periodically be requalified to perform assigned security-related tasks and duties for both normal and contingency operations. The training program for the security force at the GROA will involve classroom and exercise modules, including firearm training and qualification. Refresher training courses will be conducted annually. Training for those providing offsite assistance, as identified in the Physical Protection Plan, will be accomplished by preparation for, and participation in, coordinated exercises.

3.5 PHYSICAL BARRIER SUBSYSTEMS

[NUREG-1804, Section 1.3.3: AC 5]

The protected area of the GROA will be surrounded by physical barriers as defined in 10 CFR 73.2. Waste will be handled only within the protected area. Physical barriers will control areas within which authorized activities and conditions are permitted and will channel people, vehicles, and materials to and from access control points. The barriers will delay or deny unauthorized penetration attempts by persons, vehicles, or materials; assist detection and assessment; protect against the unauthorized removal of material, including theft; and be sufficient to allow a timely response by the onsite security force and, when necessary, by a designated offsite response force, including a local law enforcement agency to prevent unauthorized acts. The Physical Protection Plan will address how the physical barrier systems will be modified as the various waste handling facilities are phased into operation.

Access to nuclear material will require passage through or penetration of two physical barriers, one barrier at the perimeter of the protected area and one barrier offering substantial penetration resistance consistent with 10 CFR 73.51(d)(1). The physical barrier at the perimeter will be installed so that it cannot be lifted to allow an individual to crawl under it. The barrier offering substantial resistance to penetration will be described in the Physical Protection Plan.

The plan will describe (1) the size and location of isolation zones, (2) access points through the protected area barrier, (3) the manner in which access points are used, and (4) the means to control and protect access to ensure the integrity of the barrier. The physical barrier at the protected area perimeter will have at least 20-ft-wide isolation zones on both sides of the barrier. The isolation zones will be clear of obstacles and structures to permit assessment consistent with 10 CFR 73.51(d)(1).

The lighting system will provide sufficient illumination for monitoring, observing, and assessing activities in exterior areas within the protected area. The lighting system will permit assessment of unauthorized penetrations of or activities within the protected area, consistent with 10 CFR 73.51(d)(2). Emergency backup power will be provided for security-specific vital equipment and select protected area lighting in case normal power is lost. Illumination will be maintained during periods of darkness. Shadowing effects of structures will be considered in the layout of the lighting systems.

3.6 ACCESS CONTROL SUBSYSTEMS AND PROCEDURES

[NUREG-1804, Section 1.3.3: AC 6]

The Physical Protection Plan will describe access control subsystems and address applicable requirements for personnel access authorization for the protected area. Controls and procedures will be developed and implemented to verify the identity of people, vehicles, and materials and to initiate timely response measures to deny unauthorized entries or material removal. The plan will establish and maintain a personnel identification system to limit access to the protected area and to the controlled access areas within it.

A personnel identification system, identified in the Physical Protection Plan, will provide for unique identification of individuals granted access to the controlled access area. The Physical Protection Plan will address procedures for control of points of personnel access into the protected and controlled access areas. Consistent with 10 CFR 73.51(d)(7), these procedures will include appropriate methods of identifying individuals and verifying individual authorization. Additionally, they will include techniques for conducting searches before entry into the protected area of individuals, vehicles, and hand-carried packages for explosives or other prohibited items that could be used for radiological sabotage, consistent with 10 CFR 73.51(d)(9). The procedures will also provide protection against unauthorized removal of material, including theft. A lock control system to limit access to authorized individuals, consistent with 10 CFR 73.51(d)(7) and with the applicable guidance in Regulatory Guide 5.12, will be a part of the physical barrier system.

Records of access control will be retained, in accordance with 10 CFR 73.51(d)(13), for 3 years after the record is generated or until the NRC terminates the license.

3.7 DETECTION, SURVEILLANCE, ALARM SUBSYSTEMS, AND PROCEDURES

[NUREG-1804, Section 1.3.3: AC 7]

The Physical Protection Plan will describe methods for detection, surveillance, and alarm subsystems within the protected area. Detection, surveillance, alarm subsystems, and implementing procedures will provide for real-time capabilities to detect, assess, and communicate any attempted unauthorized access or penetration by individuals, vehicles, or materials so that the security force can prevent such access or penetration. Detection, surveillance, and alarm subsystems will comply with the requirements of 10 CFR 73.51(d)(3) and with applicable guidance in Regulatory Guide 5.44.

The physical protection system will have an active intrusion detection system at the protected area perimeter. The isolation zone will be monitored to detect the presence of individuals or vehicles within the zone. The intrusion detectors and associated alarm systems will be installed to cover the entire perimeter of the protected area barrier. Sensors will be positioned to overlap so that there are no gaps in the coverage of the perimeter of the protected area. The intrusion detection system will also provide coverage behind each gate and other access point in the physical barrier to the protected area. The perimeter of the protected area will be under continuous surveillance by video systems or by members of the security force. The protected area perimeter will be divided into multiple segments that are independently alarmed and monitored to assist the security force in assessing and responding to an alarm by localizing the area in which the alarm is initiated.

The primary alarm station will have bullet-resisting walls, doors, ceilings, and floors, and the interior will not be visible from outside the protected area. The Physical Protection Plan will describe the location, construction, and characteristics of the primary and secondary alarm stations, consistent with 10 CFR 73.51(d)(3). Alarms will annunciate in a continuously manned primary alarm station located within the protected area and in at least one additional, continuously staffed, independent, secondary alarm station to ensure that a single act cannot remove the capability of calling for assistance or responding to an alarm. The secondary alarm station will have some security equipment that is redundant to the primary alarm station and will also be located within the protected area. Alarms indicating penetration, including the unauthorized opening of access points, will annunciate in both the primary and secondary alarm stations. Consistent with 10 CFR 73.51(d)(11), intrusion detection systems and supporting subsystems will be equipped with tamper indicating devices and line supervision.

Access to the alarm stations will be controlled, and the primary alarm station functions will not include operational activities that could interfere with the execution of alarm response functions. The annunciation systems will indicate the status of alarms and alarm zones in the primary alarm station. Physical protection systems will be maintained in operable condition, and timely compensatory measures will be implemented in the event of system outages. In addition, consistent with 10 CFR 73.51(d)(4), the protected area will be monitored by daily, random patrols. The number of patrols per shift will be addressed in the Physical Protection Plan or implementing procedures.

3.8 COMMUNICATION SUBSYSTEM
[NUREG-1804, Section 1.3.3: AC 8]

The Physical Protection Plan will describe the communication subsystem, in accordance with the requirements of 10 CFR 73.51(d)(8). The communication subsystem will provide notification of attempted unauthorized intrusion into the protected area to the security force in each continuously manned alarm station. These personnel will be capable of calling for assistance and response forces. The primary and secondary alarm stations will be equipped to communicate with designated offsite response forces, including local law enforcement agencies.

Redundant systems will be provided to ensure the capability of communications between the security force and the designated offsite response force, in accordance with 10 CFR 73.51(d)(8). The communication subsystem will be maintained in operable condition.

3.9 EQUIPMENT OPERABILITY AND COMPENSATORY MEASURES
[NUREG-1804, Section 1.3.3: AC 9]

Test and maintenance programs for the physical protection systems will be implemented. After installation, security equipment will be initially and periodically tested to demonstrate its ability to meet the manufacturer’s operating specifications and the physical protection needs. Periodic tests and inspections will be conducted to ensure the continuing integrity of barriers and the operability of security equipment. Tests and preventive maintenance procedures will provide confidence that security equipment is effective, available, reliable, and able to perform when needed, consistent with the requirements of 10 CFR 73.51(d)(11). The testing program for the perimeter intrusion detection system will be consistent with the applicable guidance contained in Regulatory Guide 5.44.

To verify the integrity of physical barriers, the protected area, including movable openings such as gates, will be patrolled daily at random intervals by members of the security force. Verification of the functional performance of lighting, security alarms, and annunciators, including transmission to the primary alarm station, will be performed, as required. The alarm system will be tested periodically to confirm alarms in both the primary alarm station and the secondary alarm station. Timely compensatory measures will be taken when integrity or performance measures are found to be deficient, in accordance with 10 CFR 73.51(d)(11).

3.10 SAFEGUARDS CONTINGENCY PLAN

[NUREG-1804, Section 1.3.3: AC 10]

A Safeguards Contingency Plan will be developed, maintained, and periodically reviewed and revised, consistent with the requirements of 10 CFR 73, Appendix C. The Safeguards Contingency Plan and the implementing procedures will describe measures to provide predetermined responses to safeguards contingency events, so that an intruder will be engaged and impeded until offsite assistance arrives, and will include procedures incorporating a responsibility matrix as required by 10 CFR 73.51(d)(10) and Appendix C. The implementing procedures may be inspected by the NRC staff on a periodic basis. The Safeguards Contingency Plan will identify specific objectives in the event of threats, theft, or radiological sabotage. The Safeguards Contingency Plan will also specify the actions to be taken by repository management and the security force at the GROA. The Safeguards Contingency Plan will contain, among other items:

- A predetermined set of decisions and actions to satisfy the objectives
- Identification of the data, criteria, procedures, and mechanisms necessary to efficiently implement the decisions
- Identification of the individual, group, or organizational unit responsible for each decision and action.

Documented response arrangements will be made with a designated offsite response force, consistent with the requirements of 10 CFR 73.51(d)(6). In the event that the designated offsite response force is privately contracted, it will meet the requirements of 10 CFR 73, Appendix B. The Safeguards Contingency Plan will be maintained and updated, as necessary, until the NRC terminates the license. If any portion of the Safeguards Contingency Plan is superseded, the superseded portion will be kept on file for 3 years after the effective date of the change or until termination of the license, as required by 10 CFR 73.51(d)(10).

3.11 REPORTING OF SAFEGUARDS EVENTS

[NUREG-1804, Section 1.3.3: AC 11]

Safeguards events will be reported to the NRC, consistent with the requirements of 10 CFR 73, Appendix G. The Physical Protection Plan will identify those events that are required to be reported within 1 hour of discovery, followed by a written report within 60 days. The plan will also require identification of events to be recorded in the safeguards event log within 24 hours of discovery.

3.12 RECORDS RETENTION

[NUREG-1804, Section 1.3.3: AC 4(5)]

Records related to physical protection will be retained in accordance with the requirements of 10 CFR 73.51(d)(13). Consistent with 10 CFR 73.51(d)(13), the following documentation will be retained as records for 3 years after the records are created or until termination of the license: (1) a log of individuals granted access to the protected area; (2) screening records of members of the security organization; (3) a log of all patrols; (4) a record of each alarm received, identifying the type of alarm, location, date and time when received, and disposition of the alarm; and (5) the Physical Protection Program review reports.

3.13 GENERAL REFERENCES

60 FR 19825. Classified National Security Information. Executive Order 12958.

Freedom of Information Act. 5 U.S.C. 552.

Regulatory Guide 5.12. 1973. *General Use of Locks in the Protection and Control of Facilities and Special Nuclear Materials.* Washington, D.C.: U.S. Nuclear Regulatory Commission. TIC: 235802.

Regulatory Guide 5.44, Rev. 3. 1997. *Perimeter Intrusion Alarm Systems.* Washington, D.C.: U.S. Nuclear Regulatory Commission. TIC: 242395.

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4. MATERIAL CONTROL AND ACCOUNTING PROGRAM

This section of the license application addresses the requirements of 10 CFR 63.21(b)(4) by providing a description of the Material Control and Accounting Program, which meets the requirement of 10 CFR 63.78 and incorporates the requirements contained in applicable portions of 10 CFR Part 74. The general description provided in this section is suitable for public disclosure.

A Material Control and Accounting Program, compliant with applicable portions of 10 CFR Part 74, will be submitted to the U.S. Nuclear Regulatory Commission (NRC) no later than 180 days after the NRC issues a construction authorization.

The U. S. Department of Energy (DOE) will withhold the Material Control and Accounting Program Plan from public disclosure, in accordance with Executive Order 12958 (60 FR 19825), and applicable exemptions set forth in the Freedom of Information Act (5 U.S.C. 552).

The Material Control and Accounting Program will include design basis information and assess potential impacts of the program on design features. The Material Control and Accounting Program will use written procedures to account for and control spent nuclear fuel (SNF) and high-level radioactive waste (HLW) until the NRC terminates the license and the repository is closed. This program will describe, establish, implement, and maintain procedures to protect against, detect, and respond to the potential loss of SNF and HLW, including loss through possible theft or diversion. The Material Control and Accounting Program will initiate timely detection, notification, response, and recovery operations in the event of a loss of special nuclear material. This program will confirm the receipt and onsite inventory of special nuclear material with an emphasis on system capabilities for loss detection and response.

The DOE will identify, control, and account for the material that it is authorized to possess. The Material Control and Accounting Program will be designed and maintained to provide:

- Accurate and current knowledge of SNF and HLW inventory at the repository with respect to unique identities of containers, locations, and quantities

- Annual confirmation of special nuclear material inventory, as documented in the material control and accounting records, and detection of any loss or discrepancy, including possible indicators of potential theft or diversion in compliance with 10 CFR 72.76(a) and 10 CFR 72.72(b). Semiannual confirmation will be conducted on items that meet the NRC definition of strategic special nuclear material

- A collusion protection program, which includes checks and balances sufficient to detect falsification of data and reports that could conceal a potential theft or diversion, in order to thwart attempts by an insider to divert special nuclear material

- Timely investigation of, response to, reporting of, and remedial actions for indications of missing special nuclear material

- Timely reporting of accidental criticality.

This section provides information that addresses specific regulatory acceptance criteria in Section 1.4.3 of NUREG-1804. The information presented in this section also addresses applicable requirements contained in 10 CFR Part 63 and 10 CFR Part 72. The following table lists the information provided in this section, the corresponding regulatory requirements, and the applicable acceptance criteria from NUREG-1804.

GI Section	Information Category	10 CFR Reference	NUREG-1804 Reference
4.1	Material Balance, Inventory, and Record-Keeping Procedures	63.51(a)(3) 63.21(b)(4) 63.78 72.72(a) 72.72(b) 72.72(c) 72.72(d) 72.74 74.4	Section 1.4.3: Acceptance Criterion 1 Acceptance Criterion 2
4.2	Reports of Accidental Criticality or Loss of Special Nuclear Material	63.21(b)(4) 63.78 72.74	Section 1.4.3: Acceptance Criterion 2
4.3	Material Status Reports	63.21(b)(4) 63.78 72.72(b) 72.76(a)	Section 1.4.3: Acceptance Criterion 3
4.4	Nuclear Material Transfer Reports	63.21(b)(4) 63.78 72.78(a)	Section 1.4.3: Acceptance Criterion 4

4.1 MATERIAL BALANCE, INVENTORY, AND RECORD-KEEPING PROCEDURES

[NUREG-1804, Section 1.4.3: AC 1, AC 2]

4.1.1 Program Provisions and Requirements

[NUREG-1804, Section 1.4.3: AC 1(1)]

Consistent with 10 CFR 72.72(a), the Material Control and Accounting Program will ensure that the material balance, inventory, and record-keeping procedures for SNF and HLW are implemented and effectively managed. The design for the program will be based upon the design of the repository, including the Physical Protection Plan discussed in Section 3. The material control and accounting features will be integrated, as appropriate, with repository design features and operations. The DOE will account for and control special nuclear material received at the repository, as a component of SNF and HLW, through receipt, processing, aging, and emplacement, until closure of the repository. In the event that SNF or HLW is transferred from the repository, the DOE will account for such transfer. The DOE will:

- Determine special nuclear material quantities associated with receipt of SNF and HLW transportation casks
- Maintain an item-control program for identifying and tracking casks, canisters, waste packages, individual fuel elements, and individual items containing special nuclear material, as appropriate
- Maintain traceability between receipt of items and emplacement
- Maintain accounting ledgers that show current special nuclear material inventory
- Maintain enhanced control and accountability of any strategic special nuclear material from its arrival through emplacement
- Control and record item movements, including item investigation and resolution
- Maintain enhanced access control to strategic special nuclear material that meets the NRC definition of Category IA or IB material as defined in 10 CFR 74.4.
- Use tamper-indicating devices where required
- Store and control unused tamper-indicating devices
- Maintain records associated with tamper-indicating device issuance, usage, and disposal
- Maintain physical inventories and material balances
- Establish a record-keeping system
- Perform routine assessments of any SNF or HLW transfers from the repository.

4.1.2 Item Accounting and Physical Inventories

[NUREG-1804, Section 1.4.3: AC 1(3)]

Accounting for SNF and HLW will be achieved by means of item identification and tracking. The program will describe the system for tracking the receipt, identification, location, and disposition of all items. Special nuclear material will be added to the inventory upon receipt of a shipment of SNF or HLW. The quantity of special nuclear material will be accounted for based on shipment records. The continued validity of assigned special nuclear material values of the SNF and HLW within a container will be ensured by the fact that items are encapsulated or sealed with a tamper-indicating device. Waste forms received in seal-welded canisters will be regarded as encapsulated waste.

Confirmation of the presence of SNF or HLW within a container will be accomplished through verification of container integrity and verification of unique container identification numbers for welded containers and verification of the integrity of the installed tamper-indicating devices for nonwelded containers. It is not intended that seal-welded canisters be opened for material control and accounting purposes. If a canister is opened, accountability/verification will be by item accounting.

Tamper-indicating devices will be used only on nonwelded canisters (i.e., bolted casks) in a manner that ensures a clear indication of any violation of the integrity of the canister. The purpose of using the tamper-indicating device is to provide an acceptable means for confirming that the contents of a container have not changed since the tamper-indicating device was applied.

Consistent with 10 CFR 72.72(b), the DOE will conduct physical inventories at intervals not to exceed 12 months, unless directed otherwise by the NRC, to account for all SNF and HLW containing special nuclear material at the repository. The continued validity of the total special nuclear material quantity assigned to loaded drifts will be ensured by tamper-indicating devices applied to the emplacement access doors or other controls, as appropriate, which will eliminate the need to check identities of individual waste packages after emplacement within the drifts. The DOE will have an ongoing confirmation program to verify the presence of strategic special nuclear material in assigned locations. Copies of inventories will be maintained as records until the license is terminated.

4.1.3 Quality of Physical Inventories

[NUREG-1804, Section 1.4.3: AC 1(4)]

The program will require that policies, practices, and procedures be designed and implemented to ensure the quality of physical inventories and the control and maintenance of records and documentation associated with the physical inventories, as well as pertinent material balances, item control, and traceability of items between receipt and emplacement.

Any accidental criticality or any loss of special nuclear material will be reported to the NRC in accordance with 10 CFR 72.74. The program will give priority to the investigation and resolution of indications that special nuclear material is missing. A cause or probable cause will be determined and assigned to each indication of possible loss.

4.1.4 Periodic Program Assessment

[NUREG-1804, Section 1.4.3: AC 1(1)]

Procedures will require that assessments of the Material Control and Accounting Program be performed no less frequently than 24 months between any two consecutive assessments to ensure the quality of physical inventories, material balances, and the effectiveness of the overall program. These assessments will be conducted by two or more individuals who are independent of the material control and accounting function. Audit activities will encompass the entire system and will include but not be limited to review and assessment for:

- Accuracy and reliability of the accounting records with respect to SNF and HLW in terms of quantities, item identities, and locations
- Timeliness and reliability of record keeping and of the tracking of the movement of items

- Adequacy and reliability of the tamper-indicating devices in terms of the control, use, and disposal of tamper-indicating devices and the records associated with the tamper-indicating devices

- Training and qualification of personnel within the material control and accounting department.

4.1.5 Procedures

[NUREG-1804, Section 1.4.3: AC 1(1), (5)]

Material control and accounting procedures will be established, tested, maintained, and followed. Consistent with 10 CFR 72.72(c), copies of material control and accounting procedures used to conduct physical inventories will be maintained as part of the inventory record until the NRC terminates the license.

4.1.6 Collusion Protection Program

[NUREG-1804, Section 1.4.3: AC 1(6), AC 2(1)]

The Material Control and Accounting Program will have a collusion protection program to thwart attempts by an insider to divert SNF and HLW. That program will be designed to provide confidence in the integrity of the traceability of the item accounting methods, to detect falsification of data and reports, and to protect against theft or diversion by insiders acting individually or in collusion. The program will include procedures that provide for the use of:

- A two-person rule when records are created for documenting item identification and tamper-indicating devices

- Redundant and separate transaction records

- A two-person rule when nuclear material is moved to or from assigned locations

- Identification and elimination of possible diversion pathways through conduct of diversion-path analyses

- A personnel qualifications process (e.g., security clearances and background checks)

- Access control

- Material control and accounting system performance testing.

4.1.7 Records

[NUREG-1804, Section 1.4.3: AC 1(2), (7)]

The material control and accounting record-keeping program will establish, maintain, and protect records in accordance with 10 CFR 72.72(d). The record-keeping program will provide a means to assess the performance of the material control and accounting system and to inspect for compliance with regulatory requirements. Duplicate sets of records will be maintained at separate locations so that a single event does not destroy both sets. Thus, in the event of loss or destruction of either set of material control and accounting records, the other set will be available for reconstruction of the lost documentation.

Material control and accounting records will be maintained within the material control and accounting system. Some records and information will be maintained in the form of hard copy or other appropriate media. Moreover, periodic printouts will include ledgers and item control area holdings and may be used as redundant copies.

Records for waste receipt, inventory (including location), disposal, acquisition, and transfer of SNF and HLW, including maintenance of inventory during any retrieval operations, will be documented. The records will provide information about the waste form, waste package, characteristics of any encapsulation material, radionuclide characteristics, heat generation rate, and history of the waste form.

The following information will be included in the retained records:

- Name of shipper
- Estimated quantity of radioactive material per item, including HLW
- Item identification and seal number
- Aging or emplacement location
- Onsite movement of each fuel assembly or waste form canister
- Ultimate disposal.

Records will be maintained on site from the time that the material arrives at the repository until 5 years after the repository is closed. After that time, the DOE will maintain the records in a manner that ensures their usability for future generations in accordance with 10 CFR 63.51(a)(3)(ii).

Consistent with 10 CFR 72.72(b) and (c), respectively, a copy of each current inventory and a copy of the current material control and accounting procedure will be used to document that inventory is retained until the NRC terminates the license. Although it is not anticipated that SNF or HLW will be transferred out of the repository, records related to any such material transfer will be preserved for a minimum of 5 years after transfer in accordance with 10 CFR 72.72(d).

4.2 REPORTS OF ACCIDENTAL CRITICALITY OR LOSS OF SPECIAL NUCLEAR MATERIAL

[NUREG-1804, Section 1.4.3: AC 2(2), (3), (4)]

The material control and accounting procedures will identify documentation requirements for reporting, investigating, and resolving missing special nuclear material and reporting of accidental criticality events. The reporting procedures will require that any potential anomalies be reported to the NRC. Potential anomalies include, but are not limited to, indicators at alarm levels such as those reflecting off-normal conditions or situations. Such anomalies could suggest a likelihood that special nuclear material may be missing, whether or not the cause is deliberate. The anomaly-reporting system will enable prompt response to alarms indicating a loss of special nuclear material and allow determination of whether the unusual observable condition is caused by an actual loss or by a system error. The reporting procedure and resolution process will identify the anomaly and the cause so remedial action can be taken. The response will be timely to ensure that indicators that might result from diversion, loss, or other misuse are investigated and resolved promptly. Examples of potential anomalies that would initiate procedures for reporting, investigating, and resolving anomalies include:

- Missing items
- Falsified special nuclear material records
- Violation of the two-person rule
- Unrecorded or unauthorized movements of special nuclear material items
- Indications of unauthorized entry into special nuclear material item control areas, as appropriate
- Broken tamper-indicating devices, compromised container integrity, or compromised encapsulation.

Procedures will be developed and maintained through the Material Control and Accounting Program to ensure that any accidental criticality or loss of special nuclear material is reported to the NRC Operations Center within 1 hour (using the emergency notification system), in accordance with 10 CFR 72.74. If the emergency notification system is inoperative or unavailable, the required notification will be made by telephone or by any other method that ensures that the NRC Operations Center receives a report within 1 hour of discovery. Review and approval requirements and document custodial responsibility will also be defined. Reports concerning accidental criticality and loss of special nuclear material will be maintained until the license is terminated.

4.3 MATERIAL STATUS REPORTS

[NUREG-1804, Section 1.4.3: AC 3]

Procedures will be developed to require that a material status report, in computer-readable format, be completed by the material control and accounting staff and submitted to the NRC, in accordance with the instructions in NUREG/BR-0007 (Collins 2003a) and *Personal Computer Data Input for NRC Licensees* (NAC International 2001). Information on the amount of special nuclear material possessed, received, transferred, disposed of, or lost will be reported. In accordance with 10 CFR 72.76(a), a material status report will be filed within 60 days of beginning the physical inventory required by 10 CFR 72.72(b), unless specified otherwise by the NRC. Physical inventory values will be based on the most recent physical inventory taken and on subsequent inventory changes reflected in transaction reports.

4.4 NUCLEAR MATERIAL TRANSFER REPORTS

[NUREG-1804, Section 1.4.3: AC 4]

Auditable records pertaining to receipt and disposal of SNF and HLW sufficient to demonstrate that reporting requirements have been met will be retained until the NRC terminates the license. The material control and accounting procedures will specify the form in which those records are kept and provide safeguards against tampering with or the loss of records. The procedures will require that, whenever special nuclear material is transferred or received, a nuclear material transaction report is completed in computer-readable format, in accordance with the instructions in NUREG/BR-0006 (Collins 2003b) and in *Personal Computer Data Input for NRC Licensees* (NAC International 2001), as required by 10 CFR 72.78(a).

4.5 GENERAL REFERENCES

60 FR 19825. Classified National Security Information. Executive Order 12958.

Collins, C.A. 2003a. *Instructions for the Preparation and Distribution of Material Status Reports (DOE/NRC Forms 742 and 742C)*. NUREG/BR-0007, Rev. 5. Washington, D.C.: U.S. Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguards.
ACC: MOL.20050825.0276.

Collins, C.A. 2003b. *Instructions for Completing Nuclear Material Transfer Reports (DOE/NRC Forms 741 and 740M)*. NUREG/BR-0006, Rev. 6. Washington, D.C.: U.S. Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguards. ACC: MOL.20050825.0277.

Freedom of Information Act. 5 U.S.C. 552.

NAC (Nuclear Assurance Corporation) International 2001. *Personal Computer Data Input for NRC Licensees.* NMMSS Report D-24. Norcross, Georgia: Nuclear Assurance Corporation International. TIC: 253781.

5. SITE CHARACTERIZATION

The U.S. Department of Energy (DOE) began the formal program of site characterization at Yucca Mountain in 1988, consistent with the provisions of Section 113 of the Nuclear Waste Policy Act of 1982, as amended (42 U.S.C. 10133). The site characterization plan (DOE 1988a) described comprehensive studies to gather the information needed for a comparative evaluation of the site with regard to U.S. Nuclear Regulatory Commission (NRC) regulations, U.S. Environmental Protection Agency standards, and DOE siting guidelines (10 CFR Part 60, 40 CFR Part 191, and 10 CFR Part 960, respectively) that were in effect at the time. Comments on the plan by the NRC staff established the framework for further interactions between the DOE and the NRC that continued throughout the site characterization program (NRC 1989). The site characterization program conducted between 1988 and 2001 included surface based and underground tests, laboratory studies, and design and modeling activities necessary to provide the technical basis for evaluating repository performance. The site characterization information reported in the *Yucca Mountain Site Description* (BSC 2004a), has been supplemented by additional information collected by the DOE, the U.S. Geological Survey, Nye County, and others since 2002. Results of the investigations and analyses presented in this chapter include these additional studies of the geology and hydrology of Yucca Mountain as well as updated evaluations of volcanic and seismic information.

This section provides information that addresses the requirements contained in 10 CFR 63.21(b)(5) for a description of work conducted to characterize Yucca Mountain. This section also provides information that addresses specific acceptance criteria in Section 1.5.3 of *Yucca Mountain Review Plan, Final Report,* NUREG-1804. The following table lists the information presented in this section, the corresponding regulatory requirement, and the applicable acceptance criteria from NUREG-1804.

GI Section	Information Category	10 CFR Part 63 Reference	NUREG-1804 Reference
5	Site Characterization	63.21(b)(5)	Section 1.5.3 Acceptance Criterion 1 Acceptance Criterion 2
5.1	Site Characterization Activities	63.21(b)(5)	Section 1.5.3: Acceptance Criterion 1
5.2	Summary of Site Characterization Results	63.21(b)(5)	Section 1.5.3: Acceptance Criterion 2

5.1 SITE CHARACTERIZATION ACTIVITIES
[NUREG-1804, Section 1.5.3: AC 1]

This section provides an overview of the development and implementation of the site characterization program. Data available prior to formal site characterization that were used as the basis for developing the environmental assessment and the site characterization plan are discussed. Thereafter, a brief description of the performance allocation process adopted by the DOE and endorsed by the NRC during development of the site characterization plan is provided. This process was used to guide the development of testing programs that were focused on providing the data needed to evaluate the natural and engineered barriers that were expected to contribute to the performance of the repository. See Figure 5-1 for a schematic illustration of the multiple barrier repository system. The content of the site characterization plan is summarized; the status of site characterization at the time of the site recommendation (2002) is reviewed; and testing and monitoring since the Site Recommendation is discussed. Site characterization ended on February 14, 2002, with the Secretary of Energy's decision to recommend Yucca Mountain as the site for a monitored geologic repository for spent nuclear fuel and high level radioactive waste.

Information related to scientific investigations prior to the beginning of site characterization, as well as site characterization activities specific to the Yucca Mountain Project, is available in *Environmental Assessment Yucca Mountain Site, Nevada Research and Development Area, Nevada* (DOE 1986a); *Site Characterization Plan Yucca Mountain Site, Nevada Research and Development Area, Nevada* (DOE 1988a); and *Site Characterization Plan Overview, Yucca Mountain Site, Nevada Research and Development Area*, *Nevada* (DOE 1988b). Information continued to be collected after site characterization ended on February 14, 2002. A discussion of the types of information that were collected is found in Section 5.1.6.

5.1.1 Site Studies Prior to Development of the Site Characterization Plan

Information about the geologic history and conditions in the Yucca Mountain region has been collected since the early 1900s: first to support exploration for mineral and energy resources, and later to support government activities at the Nevada Test Site. Investigations were conducted prior to the Nuclear Waste Policy Act to evaluate the Nevada Test Site and contiguous areas for sites suitable for a geologic repository (DOE 1986a, Volume 1, Chapter 2, p. 2-1). This Nevada Test Site screening program led to selection of welded tuff as the preferred host rock, and the Yucca Mountain site as the preferred location (Sinnock and Fernandez 1982; Sinnock and Fernandez 1984). Geologic and hydrologic investigations were conducted to collect information about site suitability.

Some of the first site-specific investigations began in 1965, with the DOE-sponsored effort to map the Nevada Test Site at 1:24000 (Lipman and MacKay 1965; Christiansen and Lipman 1965). Work that was more focused on finding a waste disposal site commenced in 1978 with the drilling of a series of test holes. In the early 1980s, the DOE conducted reconnaissance earth-science studies. These studies included drilling five deep boreholes, to investigate stratigraphy and rock properties at depth, with one borehole penetrating into the Paleozoic carbonate rocks beneath the volcanic section. Six deep boreholes were drilled to obtain hydrologic data, and these also contributed to the knowledge of stratigraphy and lateral continuity to the volcanic rocks. 16 boreholes were drilled to broaden the database on the elevation of the water table, and to monitor any subsequent changes in its elevation. Nine boreholes were drilled to study water and gas movement and distribution in the unsaturated zone. Approximately 40 trenches and test pits were excavated to locate fault traces, or to determine the number of Quaternary events and amounts of offset. Another 54 test pits were dug to investigate Quaternary stratigraphy and soil development. This database allowed for publication of an environmental assessment (DOE 1986b; DOE 1986a) that led to nomination of the site and the development of a detailed site characterization plan (DOE 1988a).

5.1.2 Performance Allocation

The DOE used two organizing principles for site characterization: an issues hierarchy and a general strategy for issue resolution (DOE 1988b, p. 89). The issues hierarchy was a three-tiered framework used to organize and describe the information needed to address the principal regulatory requirements for a repository. This framework was used to plan the site characterization program and to explain why the program was expected to provide a technical basis for developing a license application. It was also designed to facilitate interactions between the DOE and the NRC on critical questions about the design and performance of the repository (DOE 1988b, p. 90).

The second organizing principle was the strategy for issue resolution, which was developed on the basis of a performance allocation process. The performance allocation had four steps (DOE 1988b, pp. 91 and 92):

- Develop a preliminary licensing strategy
- Identify performance measures
- Identify information needs
- Develop testing strategies to produce the needed information.

Existing knowledge about the site, and preliminary indications of the barriers that would be important to performance, were used to develop the licensing strategy and to proceed through the performance allocation steps (DOE 1988b, pp. 91 and 92).

To complete the process of issue resolution, the final steps in the strategy included data collection and analysis, as well as documentation of issue resolution. Prior to November 2001, in accordance with 10 CFR 60.18(g), and thereafter in accordance with 10 CFR 63.16(b), the DOE provided semiannual reports of progress to the NRC. These reports informed the NRC of new testing results and the results of modeling and analytical work. Frequent staff-level interactions at varying levels of formality—such as technical exchanges, less formal site visits as described by Barrett and Virgilio (1999, p. 2), and teleconferences—were also important to ensure that the NRC staff had access to the advancing understanding of Yucca Mountain and the designs that were being developed for the engineered repository components. The DOE intended the issue resolution process to be iterative if comments from the NRC or testing results led the DOE to consider the need for change (DOE 1988b, p. 96).

The DOE organized the site characterization plan (DOE 1988a) around the site-specific information needs that resulted from this process and framework. The information needs were comprehensive, covering repository design and performance for both the preclosure and postclosure periods. The objectives were to use the information obtained from site characterization to determine whether the Yucca Mountain site was suitable for development of a repository and, if so, to provide the data needed for licensing and for the design of the repository.

5.1.3 Overview of the Site Characterization Plan

The overall purpose of the site characterization plan (DOE 1988b, p. 3) was as follows:

- Describe the Yucca Mountain site and support preparation of a preliminary design for the engineered system

- Identify the issues to be resolved during site characterization and the information needed to resolve the issues

- Describe plans for obtaining the information needed to resolve outstanding issues and reduce uncertainties.

Requirements and guidance for the content of the site characterization plan were contained in the Nuclear Waste Policy Act, as amended; 10 CFR Part 60; and Regulatory Guide 4.17. The NRC was responsible under the Nuclear Waste Policy Act, as amended, and 10 CFR 60.18 (now 10 CFR 63.16), for reviewing the site characterization plan and for providing comments. These comments were provided in August 1989 as NUREG-1347 (NRC 1989). The DOE systematically addressed the NRC concerns and comments and revised testing plans, or implemented other actions, as necessary, to resolve each concern or comment.

The site characterization plan was prepared in two parts. Part A described the geologic conditions of the site and region, the geoengineering properties of the rock units at the site, the hydrologic and geochemical processes and conditions at the site, the climate and meteorology, and the designs for the repository and waste package. Part B described the site characterization program and the issue-resolution strategies that provided the basis for the program. The site characterization plan text included descriptions of planned testing and design activities for the repository, seals, and waste packages, as well as plans for assessment of repository performance (DOE 1988b, p. 3).

The geologic history of Yucca Mountain was reasonably well understood at the time of issuance of the site characterization plan. Geologic phenomena of special interest to performance were faulting, seismicity, and volcanic activity. The information that was needed to improve the understanding of these phenomena was recognized to be important for assessing the probability of disruptive events when predicting long-term repository performance. For volcanic activity, testing and analysis studies were developed to identify the location, age, volume, geochemistry, and geologic setting of past volcanic activity in the area for use in assessment of volcanic hazards. Characterization studies for seismicity and faulting were focused on estimating the potential sizes and frequencies of future earthquakes and levels of ground motion, as well as fault displacement that might affect the repository.

Knowledge of the general geometry and composition of rock units that make up Yucca Mountain was sufficient for selection of the preferred repository horizon, which is an ash-flow unit called the Topopah Spring Tuff. A database for geoengineering properties for the rock units was developed from laboratory tests on cores and field tests at analogue sites. The site characterization plan noted that additional site-specific data were needed for repository design.

Locating the repository horizon in the unsaturated zone was expected to provide a relatively benign and stable environment, but also presented challenges in terms of characterization approaches. Thick, unsaturated zones in arid settings had previously received very limited study. The importance of hydrologic conditions and processes was tied to the effects on longevity of engineered materials, as well as potential transport of radionuclides from the waste packages. Previous hydrologic studies appraised groundwater resources and established general characteristics of the saturated zone flow systems in the region surrounding Yucca Mountain. Sources of recharge and discharge had been previously identified, and flow directions and hydraulic gradients were generally understood (DOE 1988a, Volume 2, Chapter 3). The site characterization plan acknowledged that little was known about the occurrence and movement of water in thick unsaturated fractured tuffs, and the plan presented an extensive program of field investigations, laboratory studies, and analyses to gain a comprehensive understanding of the conditions in the unsaturated zone. In this same time frame, the NRC provided specific criteria for the unsaturated hydrologic environment and provided specific regulatory criteria for unsaturated zone disposal in an amendment to 10 CFR Part 60. The technology for characterizing unsaturated zone hydrologic conditions was limited, and simulating flow in the matrix and fractures of a thick sequence of unsaturated rock layers required new models. Both technology for testing and model development received considerable attention during site characterization (DOE 2002a, Sections 4.2.1.2 and 4.2.1.3).

Characterization of surface hydrologic conditions was also necessary to support repository design. These studies included flood-recurrence intervals and flood levels at surface facility locations, in order to be useful for the design of seals and shafts.

The geochemical environment was recognized to be important because of potential effects on engineered materials, as well as the possibility that transport of radionuclides could be retarded by minerals along unsaturated and saturated zone flow paths. Minerals with high sorption capacity were known to exist in some of the rock units, providing the potential to delay transport of radionuclides. Core samples from boreholes at or near Yucca Mountain provided water and rock chemistry information. Limited water samples had been analyzed, and the site characterization plan included tests to improve the database for water chemistry, both in the repository host rock and along flow paths. Finally, the site characterization plan explained that climatic changes are important because they could affect hydrologic conditions and the amount of water that could enter the repository. Data on meteorological conditions in the vicinity of Yucca Mountain were available and had been collected since the early 1980s. The principal focus of site characterization related to climate change was directed toward determining the effects of climate changes on percolation flux and water table elevations. Efforts were also directed toward a better definition of the range of climatic conditions that should be expected over the postclosure time period.

5.1.4 Role of the Semiannual Site Characterization Progress Reports

As required by the Nuclear Waste Policy Act; 10 CFR 63.16(b); and its predecessor, 10 CFR 60.18(g), results of site characterization studies were reported regularly from 1990 to 2002 in semiannual progress reports (e.g., DOE 2001). These reports provided summary information related to waste form and waste package materials and design studies, as well as results of field and laboratory tests and other site characterization activities. When new information resulted in the need for modification of site characterization studies, or the addition of new studies, these changes were described in the reports (DOE 2001). The *Yucca Mountain Science and Engineering Report* (DOE 2002a) summarizes site characterization work and the technical basis for the site recommendation. In addition to issuing these reports, interactions between the DOE and the NRC informed NRC staff of the progress made in characterizing the site and provided the opportunity for the NRC to have input into the site characterization testing priorities.

5.1.5 Description of Pre–Site Characterization and Site Characterization Activities that Resulted in Site Recommendation

This section describes investigations of the geology, hydrology, climate, geotechnical and geomechanical properties, geochemistry, and other characteristics of the site that have been performed to determine whether Yucca Mountain is a suitable site for a repository. These investigation include extensive surface-based and underground investigations, laboratory experiments and modeling activities. The goal of these investigations was to characterize the Yucca Mountain site and provide the technical basis for an evaluation of repository performance.

From the surface, the DOE drilled more than 180 deep boreholes at Yucca Mountain and in the surrounding area. Independent scientists working for Nye County, Nevada, drilled additional exploratory holes into the geology and collaborated with DOE scientists on their findings. From 1995 to 1997, a 5-mile tunnel was mined through Yucca Mountain to function as an Exploratory Study Facility (ESF). In 1998, the DOE completed a second 2-mile cross-drift tunnel to facilitate additional experiments in the repository host rock (DOE 2002a, Section 1.3). These tunnels, and the numerous niches and alcoves carved off of them, created within Yucca Mountain an underground laboratory. These efforts were further supplemented by numerous laboratory experiments, as well as excavation of similar geologic features both nearby and at natural analogue sites around the world (BSC 2004b) and (DOE 2002a, Section 4.1.2). Through this work, the geology of Yucca Mountain and its ability to safely contain radioactive wastes became very well understood (U.S. Senate 2006, p. 6). Figures 5-2, 5-3, and 5-4 illustrate the extent of the regional explorations that were conducted.

More than 450 deep and shallow boreholes were drilled, and more than 75,000 ft of core samples and 18,000 geologic and water samples were also collected (Abraham 2002, p. 16). These activities were conducted to characterize geologic and hydrologic features and properties, as well as mechanical properties of rock units important to repository design and performance. Geochemical and isotopic studies were conducted to characterize unsaturated and saturated zone flow and transport, and to provide the basis for developing models to support performance assessment. Regional and site-specific geologic studies were also conducted to obtain the information needed to evaluate seismic and volcanic hazards. Meteorological monitoring and modeling, as well as biological and ecological investigations, were also performed (Abraham 2002, Section 6.1.3).

The single largest effort of the site characterization program was the ESF, which provided access to the subsurface environment near the approximate repository location and elevation for exploration and testing. The main underground tunnel at the ESF, which is 8 km long and U-shaped, was completed in April 1997. Figure 5-5 presents a view of the ESF at the North Ramp turn. A cross-drift across the planned width of the repository was completed in October 1998, as part of the Enhanced Characterization of the Repository Block (ECRB) Cross-Drift studies. Additional subsurface niches and alcoves have been excavated off the main drift and cross-drift tunnels to support a number of specific activities, which include (1) mapping faults and fractures;

(2) collecting rock samples to determine geotechnical properties; (3) ambient hydrologic testing; and (4) conducting a large thermal test to observe the effects of heat on the hydrologic, mechanical, and chemical properties of the rock, as well as the chemical properties of the water and gas liberated as a result of heating. This information has been used for developing, calibrating, and validating the models that represent site processes and conditions (DOE 2002a, Section 1.3.1).

The data collected from Yucca Mountain and related studies were compiled into a comprehensive assessment of the repository's predicted performance. As more data were collected, this performance assessment was continually refined. All this study and analysis information was subjected to critical peer review.

The results of these comprehensive site characterization activities culminated in the site recommendation (Abraham 2002). As evidence of the scientific basis for going forward with the Yucca Mountain site, the recommendation contained a comprehensive 850 page *Yucca Mountain Science and Engineering Report* (DOE 2002a), with supporting information documented in approximately 90 detailed scientific analysis and model reports (supported by many hundreds of technical documents compiled during more than 20 years of site studies) describing the behavior of the natural and engineered features of the repository. These reports, which have been updated and augmented with additional information since the end of site characterization, provided the basis for the conceptual and numerical models and analyses that are described in SAR Sections 2.3.1 to 2.3.11. They also provide the foundation for the TSPA (SAR Section 2.4.1).

The *Final Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada* (DOE 2002b, pp. 5-82 and 5-83) used the results of site characterization to show that the recommended repository would have little to no adverse affect on future populations or the environment. The environmental impact statement used the results of site characterization at Yucca Mountain to show that the site provides a combination of geologic and hydrologic features that form effective natural barriers to the flow of water and the movement of radionuclides. Furthermore, the environmental impact statement showed that the underground environments at Yucca Mountain are conducive to the design and construction of a robust and durable engineered system.

In February 2002, the Secretary of Energy recommended the site for development of the repository, and provided a comprehensive basis for site recommendation. The Secretary summarized the extensive data collection and analysis that had been completed, and concluded that the site "brings together the location, natural barriers, and design elements most likely to protect the health and safety of the public, including those Americans living in the immediate vicinity, now and long into the future" (Abraham 2002, Section 3.1).

The following sections specifically describe the site characterization testing and monitoring activities that led to the site recommendation. Figures 5-2, 5-3, and 5-4 show the locations for exploration, monitoring, and characterization that were used for the Yucca Mountain evaluation. Activities for post–site characterization are described in Section 5.1.6. Results from all activities are presented in Section 5.2.

5.1.5.1 Geology

Geologic investigations during site characterization were largely focused on improving the detail and depth of understanding of data developed during the earlier reconnaissance studies. For example, the stratigraphy of the repository horizon was subdivided into small units so that minor structures could be more easily identified and represented. Three primary stratigraphic systems have been developed to investigate the distribution of lithostratigraphic, hydrogeologic, and thermal-mechanical units at Yucca Mountain. Common to all these systems are the properties of bulk rock density, grain density, and porosity. Changes in these rock properties result in commensurate changes in many of the associated hydrogeologic and thermal-mechanical properties that define units whose boundaries coincide with a particular stratigraphic contact.

Surface mapping of faults was done at as fine a scale as 1:240, and fault trenches and other vertical exposures were remapped at finer scales. Other mapping (shallow pits) included expansion of pavement studies of fracture patterns. These were used to obtain data on the main directions and styles of fracturing in surface outcrops. The fracture mapping resulted in the identification of the principal directions of fracture formation, fracture frequency, and various fracture attributes (smoothness, attitude, fillings, termination, etc.). These studies produced numerous maps, and several summary maps (Sweetkind and Williams-Stroud 1996). Figures 5-2, 5-3, and 5-4 show the locations of exploration, monitoring, and characterization that were used for the Yucca Mountain evaluation.

Figure 5-6 illustrates the locations of exploration relative to the ESF and the repository. Geologic boreholes provided a more complete understanding of north-south variation in stratigraphy. Other boreholes were drilled to more fully characterize the unsaturated zone. Eleven shallow to intermediate depth holes were drilled along the North Ramp alignment of the ESF (Brechtel et al. 1995), in order to provide design and stratigraphic information.

Geomorphic Setting—Prior to the initiation of site characterization, long-term average upland and hill slope erosion rates had been established for the southern Great Basin, and many of the parameters necessary to estimate erosion rates in the region had been obtained from ongoing scientific studies at the Nevada Test Site (Stuckless and Levich 2007, pp. 53 to 103). Few of these data, however, were specific to the repository site. Therefore, erosion and geomorphic process studies were established to provide representative, site-specific data to support analyses of present and past locations and rates of erosion and future tectonic activity potential effects on selected other site features and processes (BSC 2004a, Section 3.4).

Cation-ratio dating of hill slope boulder deposits on Yucca Mountain, and nearby hill slopes, was used to calculate the long-term removal rate of unconsolidated material from the middle and lower Yucca Mountain hill slopes. In situ cosmogenic nuclide dating of hill slope boulder deposits was carried out to evaluate if the rock varnish cation-ratio age estimates were in reasonable agreement with the new cosmogenic nuclide exposure ages. Erosion rates on bedrock ridges were also determined for Yucca Mountain. Quaternary erosion on volcanic landforms in Crater Flat was also evaluated (BSC 2004a, Section 3.4.6). Rapid erosion may occur by rare mass-wasting events, such as occurred on July 21 and 22, 1984, when storms triggered debris flows on the south hill slope of Jake Ridge, which is located about 6 km east of the Yucca Mountain crest (Coe et al. 1997, pp. 11 to 28). Evaluation of faulting events on faults in the site area during Quaternary time (Keefer et al.

2004) were completed to understand the subtle landforms and preservation of early and middle Pleistocene deposits on Yucca Mountain hill slopes (Whitney and Harrington 1993, pp. 1008 to 1018). The exposed fault scarps along the Solitario Canyon and Northern Windy Wash faults were exposure-dated by cosmogenic ^{14}C to determine whether Holocene surface ruptures may have formed the scarps (Harrington et al. 1994, p. A303). Other studies, like the one done for the Stagecoach Road Fault, investigated prominent scarps where eolian sand has washed away from a scarp formed in a well-cemented, reworked tuff.

Tectonic Setting—Tectonic studies were designed to provide information necessary to evaluate potential disruptive events during both the preclosure and postclosure periods. Investigations were conducted to quantify the Yucca Mountain structural setting and the relationship of that setting to potential volcanism and seismicity. Figures 5-2, 5-3, and 5-4 show the locations of exploration, monitoring, and characterization that were used for the Yucca Mountain evaluation.

Dating of basaltic cinder cones was used to determine the rate of occurrence of volcanic activity during the past several million years. Magma properties and dynamics were estimated from a combination of field studies and published information on both Yucca Mountain and worldwide volcanoes, with emphasis on duration of eruption, temperature, and chemical properties. Analogue information was used to estimate probable dike length parameters (BSC 2004c, Section 6.3.2).

Quaternary fault displacement was studied in more than 60 trenches and several natural exposures; most notable of these was an exposure on the west side of Busted Butte, where a 600,000- to 700,000-year record of movement was preserved (Keefer et al. 2004, Chapter 5). The information collected included the number of events; the amounts of displacement; and, in conjunction with age determinations, recurrence intervals. The amount of displacement for a given event, together with the distance over which that event was recorded, was used to estimate magnitude (BSC 2004a, Section 4.3).

Geophysical Surveys—The DOE has made extensive use of geophysical surveying techniques to gain as complete an understanding of the repository site as possible. Geophysical surveys supplemented information from a variety of sources and methods, including scientific literature, current and historical seismicity data, geologic maps, and logs from boreholes and surface trenches. Activities included gravity surveys, aeromagnetic and paleomagnetic investigations, seismic reflection and refraction profiles, and magneto-telluric soundings. Geophysical testing studies included more than 35 km of deep regional seismic reflection profiling, about 55 km of high-resolution shallow seismic reflection profiling in the repository area, and magnetic and gravity surveys along the same 55 km. Suites of geophysical logs were obtained for the deep boreholes, and these were correlated with geologic logs. Figures 5-2, 5-3, and 5-4 include the locations of the tectonic and geophysical surveys that were conducted for Yucca Mountain evaluation.

Investigations to understand contemporary deformation and its implications for future seismicity and landform changes were undertaken. Geodolite and Global Positioning System (GPS) strain and geodetic leveling measurements were used to determine the rate of strain accumulation in 1983, 1984, and 1993. Campaign mode (aperiodic surveys) and continuous mode GPS measurements were also carried out (Keefer et al. 1997). Spectral analysis of surface waves was used to determine shear-wave velocity profiles in the ESF North Ramp and at (or near) the crest of Yucca Mountain (BSC 2002a). Figure 5-6 illustrates the locations of the spectral analysis of surface waves surveys.

Seismicity Monitoring—Studies were developed to monitor current seismic activity, and to provide information on (1) the current frequency of earthquakes in the southern Great Basin; (2) seismic wave amplitudes as a function of magnitude; and (3) attenuation as a function of distance from the source and characteristics of the local geology. Continuous operation of the Southern Great Basin Seismic Network began in 1978. The current network consists of 30 three-component digitally recorded seismic stations within a radius of about 60 km of Yucca Mountain. One station is located underground in Alcove 5 of the ESF (von Seggern and Smith 2003, p. 6-8). Figure 5-7 illustrates the locations of seismic monitoring locations. Seismic tomography of the crust and upper mantle was evaluated using velocity structure in the crust and upper mantle in the Yucca Mountain region, as determined from inversion of compressional-wave travel times from worldwide earthquakes measured at the Southern Great Basin.

Subsurface Mapping and Testing—Studies were developed to produce subsurface mapping and testing. Figure 5-8 illustrates the general layout of the underground investigation areas that were mapped and tested. The results of these studies would build upon and complement the surface-based mapping and testing studies. Activities included mapping, heated drift experiments, and hydrologic experiments. Full periphery geologic mapping and scanline surveys within the ESF provided the information used to characterize the fracture network. Excavation-induced fractures in the ESF were observed and documented. Joint sets and their sequences of formation were identified for comparison with the data derived from surface outcrops. Fracture properties, such as normal and shear stiffness, fracture strength (cohesion (c) and internal friction angle (φ)), dilation angle, and strength degradation were measured or sampled for laboratory testing to assist in engineering design.

5.1.5.2 Hydrology

Hydrology studies were developed to provide an understanding of the surface water and groundwater flow system. Groundwater is expected to be the major transport medium of radionuclides to the accessible environment. The strategy was to develop and conduct investigations to quantify the pertinent components of the hydrologic system. The results reflect the current understanding of the hydrologic properties, initial and boundary conditions and processes, and their interrelationships. The results of the hydrology studies were combined with the results of other site studies in order to produce a conceptual site model and a complete description of the site. The hydrology studies consisted of the data collection and evaluation activities that were used to describe two distinct regimes of the hydrologic system: the unsaturated zone, and the saturated zone (Figure 5-9).

Saturated Zone Flow—Saturated zone site investigation studies were developed to provide an understanding of the groundwater environment at both site and regional scales, and to construct a consistent regional conceptualization of groundwater flow.

This conceptual model would provide reliable boundary conditions that could be assigned to the site-scale geohydrologic environment, which is expected to be the major transport medium of radionuclides from beneath the repository to the accessible environment. Field and laboratory tests were conducted to evaluate the hydraulic properties of the fractured tuff and alluvium downgradient along the projected flow path. Hydrochemical and isotopic data from analyses of groundwater samples were collected in boreholes, wells, and springs in the Yucca Mountain region to provide an independent set of data from which groundwater flow patterns and rates of flow could be inferred. The hydrochemical signature of groundwater was characterized from pH, oxidation potential, partial pressure of carbon dioxide, major-ion chemistry, isotopic composition, and trace-element abundances. Controls on the isotopic composition of groundwaters differ from those that apply to the major-ion chemistry. Stable isotopes were collected to evaluate paleoclimatic indicators of time, location, and environment of recharge, plus the direction (path) of groundwater flow. The decay rates for radioactive isotopes are known, and can be used to indicate modern nuclear-age recharge as well as to date the time of prenuclear-age recharge. Major-ion chemistry and isotopic chemistry of groundwaters represent complementary approaches as indicators of regional flow and paleohydrologic conditions (SNL 2007a, Sections 6.3 and 6.5).

Several methods have been used to determine the hydraulic properties of the saturated zone. Field tests to estimate transmissivity and storativity included the following:

- Single-borehole, constant rate discharge tests (i.e., pumping tests)
- Multiple-borehole pumping tests, in which observation boreholes were used
- Constant-rate injection tests in single-borehole and multiple-borehole configurations
- Single-borehole, variable rate discharge tests
- Single-borehole, slug-injection, and slug-withdrawal tests
- Single-borehole, pressure-injection tests.

Borehole flow and temperature surveys during pumping provided information on the vertical distribution of the hydraulic properties. Because of the depth of the saturated zone at Yucca Mountain, most of the tests in the volcanic tuffs were single-borehole tests of the entire open interval or of specific depth intervals in a borehole (SNL 2007a).

Studies included the Water-Level Monitoring Program (D’Agnese et al. 1998). Figure 5-10 includes the locations of hydrology study locations that were used for the evaluation of potentiometric conditions in the Yucca Mountain, and to evaluate groundwater flow and transport. Tests in some of these boreholes included the stratigraphic intervals contributing to flow in the subsurface. Geophysical logging and flow surveys were conducted in most of the deeper boreholes at Yucca Mountain. Geophysical logs from these wells provided extensions of core results of the stratigraphic relationships, matrix properties, and indirect indicators of the vertical variation of bulk density and porosity data. Flow surveys were used to determine the intervals, and possibly the fractures, that produce water. The tests included collection of fracture orientation and inferred fracture spacing was used for development of probability distributions. Multiple intervals were tested to determine the predominant contributing flow interval in a vertical section. The tests were typically performed in conjunction with other downhole geophysical testing. Borehole televiewer logs were obtained to define the distribution of fractures in vertical sections intersected by the borehole installation. These tests identified zones that could be flowing intervals (SNL 2007a).

Hydraulic tests were conducted in boreholes/wells to obtain bulk flow properties of the area aquifers. The tested single-hole wells that provided the most useful information included USW H-1, USW H-3, USW H-4, USW H-5, USW H-6, USW G-2, USW G-4, UE-25 b#1, UE-25 p#1, USW

WT-10, UE-25 WT#12, and UE-25 J-13. Open-borehole hydraulic tests for the entire borehole length were conducted to evaluate averaged properties (Figure 5-10). In addition, hydraulic tests were conducted and hydraulic heads measured at specific packed-off intervals in selected boreholes (SNL 2007a).

In addition to the range of single hole hydrologic and geophysical observations, a number of multiwell interference tests were performed at the C-Wells Complex and at the Alluvial Testing Complex. To support the characterization of the saturated fractured tuffs, several hydraulic and tracer tests were conducted at a three-well complex (UE-25 C#1, UE-25 C#2, and UE-25 C#3, hereafter referred to as C#1, C#2, and C#3, respectively) known as the C-Wells. This complex is located approximately 2 km southeast of the repository footprint. To support the characterization of the saturated alluvium, both hydraulic and tracer testing were conducted at the Alluvial Testing Complex (ATC), centered around well NC-EWDP-19D (hereafter referred to as 19D), which is located just outside the southwest corner of the NTS, essentially right at the compliance boundary. These tests were designed to obtain hydraulic parameters on a broader scale than single-well hydraulic tests. The multiwell tests provided transmissivity, hydraulic conductivity, storativity, and specific yield data (SNL 2007a, Section 6.1). Figure 5-11 shows the location of the C-Wells Complex and the Alluvial Testing Complex.

The C-Wells Complex hydraulic testing provided results at a scale that is representative of larger areas. Point measurements conducted in other saturated zone wells investigated properties in close proximity to the tested well, whereas those conducted at the C-Wells complex scale stressed a much larger volume of rock. These tests resulted in determining representative flow and transport properties of the volcanic aquifer system. Multiple tests, including geophysical logging, borehole flow surveys, cross-hole seismic tomography, single-well packer tests, open-borehole hydraulic tests, and multiwell/cross-hole interference tests were performed at this complex to cumulatively determine a number of hydraulic properties; constant discharge tests were also performed (SNL 2007a). Figure 5-11 shows the location of the C-Wells Complex.

The Nye County Early Warning Drilling Program established a groundwater monitoring network of the saturated zone south of Yucca Mountain. Wells were completed to various depths in order to obtain geologic and hydrologic information from the volcanic, alluvial, and carbonate aquifer systems. In addition, the water level data allowed updates to the potentiometric surface map. Geophysical logs from these wells provided details of the stratigraphy, allowing comprehensive geologic cross sections to be developed by the project. The methods of data collection included exploratory geologic sampling boreholes, multiple-screened completion wells, dual completion piezometer wells, and a variety of hydraulic tests (BSC 2004d). Some of the Nye County phases were completed after Site Recommendation, and are described in Section 5.1.6.2.

Additional studies included streamflow infiltration and recharge testing to estimate the inflow contribution to the saturated zone through Fortymile Wash. These included monitoring streamflow, peak discharge, streamflow volumes, and evaluation of the groundwater elevation fluctuations in area wells (Savard 1998). Figure 5-9 shows the location of these investigations as well as the locations of U.S. Geological Survey district surface water monitoring stations that are included in the annual water year reports (e.g., USGS 1982 and Berris et al. 2003).

Saturated Zone Transport—Saturated zone transport site studies were developed to provide an understanding of those features of the groundwater environment at the site-scale, which may influence the transport of radionuclides from beneath the repository to the accessible environment (BSC 2004a, Section 8.3.2). Field and laboratory tests were conducted to evaluate the transport properties of the fractured tuff and the alluvium downgradient along the projected flow path. Tracer tests conducted at the C-Wells Complex quantified the transport characteristics of the saturated Miocene tuff. Tracer tests using conservative tracers were conducted to obtain estimates of flow porosity, matrix porosity, longitudinal dispersivity, and dimensionless matrix diffusion coefficients of the high-flow-rate Bullfrog and the low-flow-rate Prow Pass Tuffs (SNL 2007a). Figure 5-11 shows the location of the C-Wells Complex.

Laboratory batch sorption tests developed sorption isotherms for various tracer solutions to solids ratios, under several different experimental conditions. Isotherms were used to develop sorption parameters for the specific lithology tested, and for specific surrogate tracer solutions using C-Wells rock core from several stratigraphic units. The mineralogy of tuffs was quantified to evaluate sorption and retardation. The C-Wells crushed tuff column tests supported transfer of that knowledge to the field during the C-Wells tracer test, while addressing scaling on transport properties. Flow rate variances were used to identify such rate-limited effects as sorption equilibrium or diffusion-controlled sorption rates (SNL 2007a, Section 6).

Alluvial Testing Complex transport testing consisted of four single-well injection-withdrawal tracer tests conducted in NC-EWDP-19D1. Tests were conducted on 3 shallow alluvial screened intervals near the water table, and at 1 deep alluvial interval. Test times ranged from less than 1 hour to 30 days. Parameter estimates obtained from the single well tracer tests included flow porosity, specific discharge, groundwater transport velocity, longitudinal dispersivity, the colloid detachment rate, and tracer sorption (SNL 2007a, Sections 6.4 and 6.5). Figure 5-11 shows the location of the Alluvial Testing Complex. Laboratory alluvium batch sorption tests also obtained tracer concentration analyses and sorption parameters for the tracers used in the Alluvial Testing Complex tracer tests (SNL 2007a, Sections 6.4 and 6.5).

Bulk aqueous chemical analysis of the saturated zone determined the processes of groundwater evolution, to assist in determining recharge rates, flow directions and velocities, and the mixing proportions of water from different source areas. Numerous water samples were obtained and analyzed from Yucca Mountain Project wells, Nye County wells, and public wells in the vicinity of the project. Primary analyses included major cations, anions, oxidation-reduction potential, and isotopes (SNL 2007b, Appendix A).

Unsaturated Zone Flow—To provide an understanding of the unsaturated zone hydrologic system at a site-scale, investigations were conducted of the movement of water and gases through the unsaturated zone in the immediate vicinity of the repository. This information was used to characterize infiltration, percolation, multiphase flow and transport, and hydrochemistry. Site characterization for unsaturated zone flow and transport included field and laboratory testing, and was supplemented by the results from many other tests where the principal objective was geology, saturated flow, or geotechnical properties (BSC 2004a, BSC 2004e). Figure 5-8 shows the locations of underground testing alcoves and niches in the ESF and ECRB Cross-Drift.

ESF drift seepage test and niche moisture studies (BSC 2004e) were conducted to characterize the seepage process and further the understanding of how moisture could seep into drifts. The studies included measuring in situ hydrologic properties of the repository host rock, and provided a database of liquid-release and seepage data that could be used to evaluate drift-scale seepage processes to quantify the extent to which seepage is excluded from entering an underground cavity. A key objective was to determine the seepage threshold below which percolating water does not seep into a drift. The objectives of these studies were realized through a combination of field experiments, including air-injection, liquid-release, and seepage tests. Tables 5-1 and 5-2 list the types of testing, the locations conducted in the underground, and the places in the In Situ Field Properties report where these tests are discussed in detail (BSC 2004e, Tables 1-1 and 1-2). Figure 5-12 illustrates the layouts of some of the types of ambient flow tests that were conducted in the ESF and ECRB Cross-Drift alcoves and niches. Thermal tests are summarized in Section 5.1.5.3.

Site characterization studies included the drilling and instrumentation of deep unsaturated zone boreholes. These instrumented boreholes (USW NRG#4, NRG#5, NRG-6, NRG-7a, UE-25 UZ#4, UE-25 UZ#5, USW UZ-7a, SD-9, USW SD-12, and ONC-1) provided pneumatic and hydrologic properties of the geologic units of the deep unsaturated zone, and allowed measurement of in situ air pressure, water potential, and temperature at multiple depths (BSC 2004f). Study locations are shown in Figure 5-6. Pneumatic pressure was monitored in deep boreholes to evaluate bulk pneumatic properties, and to quantify the effects of barometric pressure changes deep in the unsaturated zone. Borehole temperature data were used to evaluate temperature gradients and heat flow in unsaturated zone geologic units. Water potential data quantified the potential for water movement in deep unsaturated zone hydrogeologic units (BSC 2004a, Section 7). In addition, 99 shallow boreholes were drilled for neutron probes in order to measure in situ water content.

Quantification of the hydrologic properties of the rock matrix of multiple hydrogeologic units was conducted using in situ and laboratory methods. Laboratory samples were obtained from the surface, from boreholes, and from the ESF and ECRB Cross-Drift. Determination of hydraulic properties provided hydrologic parameters using various laboratory methods (BSC 2004f, Section 6). Bulk chemistry and environmental isotopes sampling was used to determine the distribution and abundance of species from surface sources and the saturated zone. ESF sampling and analysis for environmental isotopes provided both spatially representative and structurally targeted data on distribution and abundance (SNL 2007c, Section 6.5; James et al. 1997, Section 8.3.3). Laboratory methods included measurement of bulk density, particle density, porosity, volumetric water content, saturation, water potential, saturated hydraulic conductivity, and moisture-characteristic curves.

Air-injection testing in deep surface-based boreholes was used to determine the in situ air permeability of hydrogeologic units in the deep unsaturated zone. Pneumatic testing in ESF Alcoves 1, 2, 3, 4, and 6 was used to determine the air permeability, effective porosity, and transport characteristics of the hydrogeologic units exposed in the ESF. Investigations in drifts and alcoves included numerous systematic tests, as well as investigations tailored to the specific purpose of the alcove and the rock types encountered. Table 5-1 and 5-2 illustrate the types and locations of tests in the underground. Core examination and borehole televiewer logs investigated formation fracture frequency and fracture porosity. Cross-hole tracer tests at C-Wells and the Alluvial Testing Complex provided values for transport porosity and tortuosity. Tests on physical and hydrologic properties of welded versus nonwelded and lithophysal versus nonlithophysal rocks were conducted to obtain hydrologic parameters (BSC 2004f, Section 6).

The Alcove 2 testing of the Bow Ridge Fault allowed for estimation of fault disturbed zone characteristics (fracture density, degree of brecciation, fracture fillings). The sampling of rock gas provided a measure of the degree of communication with the atmosphere, and was used to estimate fault permeability and other chemical indicators (such as age) (LeCain et al. 1997). The Alcove 4 tests included water-release seepage tests and evaluation of the capillarity of the medium. Water release tests were conducted in unfaulted and unfractured Paintbrush nonwelded (PTn), as well as in a fault (BSC 2004e, Sections 6.5 and 6.7) to evaluate water intake in the matrix as well as movement along preferential pathways (small faulted areas). The Alcove 6 tests of the Ghost Dance Fault provided pneumatic characteristics of the fault and fault zone. Borehole video and caliper logs recorded fractures and geometric features. Pore water samples were obtained from rock cores (LeCain et al. 2000). Single and cross-hole pneumatic and tracer-gas tests provided estimates of permeability, porosity, and dispersivity of the Ghost Dance Fault (BSC 2004e, Sections 6.1 and 6.5).

Physical and hydrologic properties of core samples from Yucca Mountain boreholes determined the physical and hydrologic properties of the rock matrix in multiple hydrogeologic units. Measurements of saturation and the water potential in welded versus nonwelded rocks established rock properties. Water bulk composition for pore waters extracted from core established the chemical composition of water from the matrix for various rock units and site locations (BSC 2004e, Section 6.14).

Unsaturated Zone Transport—Unsaturated zone site investigation studies were developed to provide an understanding of the physical and chemical properties of the unsaturated zone that influence the transport of radionuclides from the repository to the saturated zone. Studies included both field and laboratory tests, which were supplemented by test studies where the principal objective was geology, hydrologic flow, or geotechnical properties.

Perched water was never encountered in the ESF or ECRB Cross Drift; however, perched water was encountered in deep boreholes (UZ-1, UZ-14, SD-7, SD-9 WT-24, and NRG-7a), commonly near the contact between the Topopah Spring welded (TSw) and Calico Hills nonwelded (CHn) below the repository horizon (BSC 2004a, Section 7.4.2). Perched and pore waters were analyzed for chemical composition of water from the matrix for various rock units (including the PTn, TSw, CHn, and alluvium) and site locations. Chemistry included major, minor, and trace elements, as well as environmental isotopes. The environmental and stable isotopes helped bound the ages of the water, flux rates, and fracture coating histories. Isotopic ratios were used to investigate fracture-matrix interactions (SNL 2007c, Section 6; James et al. 1997, Section 8.3.3).

Fracture and lithophysal cavity calcite deposits provide estimates on the age of the mineral formation and order of magnitude estimations of the percolation flux. Mineral paragenesis from isotopic ratios was used to investigate the progressive growth of mineral species in order to determine the conditions of mineral formations. Fluid-inclusion studies of the calcite fracture-fillings provided inclusion formation temperatures, and were used to address the issue of potential thermal upwelling of water (BSC 2004e, Section 6.14). Isotopic analysis of calcite fracture fillings were used to evaluate the source of oxygen incorporated into the fillings, using mineral specimens obtained from various mineralized fracture environments (BSC 2004e, Section 6.14).

The Busted Butte unsaturated zone transport tests were designed to investigate the hydrologic behavior of the vitric portion of the Calico Hills Formation, and to provide access for tracer and microsphere injection and post-test characterization. Overcoring was used to determine the extent of fluid imbibition into the matrix surrounding the fracture in test beds in many of the locations. The experimental scale between different locations covered approximately one order of magnitude (e.g., the Phase 2 test block was 7 m high by 10 m wide by 10 m deep), to allow for evaluation of scale effects on transport property determination. Remote methods—such as ground-penetrating radar, electrical resistivity tomography, neutron logging, and blacklight mapping (for fluorescent microsphere tracers)—supplemented direct sampling and analysis (BSC 2004e, Section 6.13). Figure 5-13 shows the location of Busted Butte in relation to the repository. Figure 5-14 provides a schematic layout of the Busted Butte Unsaturated Zone Transport Test.

Laboratory results of tests on blocks of Calico Hills Formation excavated from the Busted Butte facility are similar to those predicted on the basis of laboratory sorption measurements on samples of crushed tuff, and with field scale measurements using nonradioactive chemical tracers (Vandergraaf et al. 2002, Section 10).

In addition to the field testing, laboratory testing was conducted to enhance understanding of the site characteristics as they relate to radionuclide transport. Thermodynamic properties of zeolites and clay minerals were used to develop the thermodynamic properties of sorptive and reactive minerals; specifically, zeolites and clay minerals that may occur along the projected radionuclide transport pathways of the unsaturated zone and saturated zone. The chemistry and mineralogy of rocks along the radionuclide transport pathway were used to obtain bulk, minor, and trace-element chemical composition of the rocks, in order to characterize the rock-chemistry expected on the radionuclide transport pathways in the matrix and/or fracture flow dominated units. Autoradiography for radionuclide sorption sites was used to determine the mineral phases responsible for sorption of radionuclides (Vaniman et al. 1996, Section 4.3). The type, amount, and distribution of clay minerals that sorb radionuclides were investigated, along with changes in physical characteristics under the influences of heat (Vaniman et al. 1996, Sections 5.5 and 5.6). The energetics of zeolite dehydration were investigated to determine their potential impact on flow and transport behavior during heated conditions (Bish 1995). A silica dissolution kinetic test was used to evaluate the dissolution-precipitation of minerals due to the interaction of fluids with the rocks (Knauss and Wolery 1988). Microbial investigations were conducted to obtain data on the impacts of microbial activity on radionuclide transport and the corrosion of the waste package material (DOE 2002a, Sections 4.2.3 and 4.2.4). Bulk chemical composition and radionuclide solubility in water from well J-13 were evaluated as a function of temperature to understand the transport of radionuclides through the unsaturated zone, saturated zone, and Engineered Barrier System (EBS). The solubility of radionuclides was measured in radionuclide-spiked J-13 water at temperatures up to 100°C, under oxidizing conditions approaching supersaturated states, and by characterizing the solid precipitants and dissolved concentration in the supernatant solution (DOE 2002a, Section 4.2.2.2.1).

Seepage Testing—These investigations focused on the mechanisms that might allow percolation flux to become seepage into the drifts at Yucca Mountain. ESF and ECRB Cross-Drift alcoves and niches were designed and built to allow in situ investigations of seepage. Pre- and post-excavation water-release seepage tests were conducted in five niches located in the ESF. After excavation, mapping, and test bed preparation, seepage collection trays were installed and water-release tests were conducted in order to determine how much seepage into the niche is realized from releasing known quantities of water from a medium that has been pneumatically characterized. Test results were used to determine seepage thresholds. Systematic hydrologic characterization, using subhorizontal boreholes in the ceiling of the drifts, was used to obtain spatially representative estimates of formation physical and hydrologic properties, and to quantify the degree of variability in those properties. Air-k tests and water-release tracer tests were conducted. Infiltration "bench tests" in the ECRB Cross-Drift were used to determine infiltration (drift drainage capacity) properties of repository horizon rock, resulting in drift drainage capacities for the rock types tested (BSC 2004e, Sections 6.1 and 6.2).

Seepage and transport tests were also conducted between Alcove 8, located in the ECRB Cross-Drift, and Niche 3, located in the ESF, to investigate how water would migrate through a fracture system over greater distances than those previously tested. Figure 5-15 shows the test bed for Alcove 8–Niche 3 tests. Water was introduced into an infiltration plot located in Alcove 8, and migration of the plume was monitored via instrumented boreholes located in the lower Niche 3. Flow paths crossed the lithophysal-to-nonlithophysal unit contacts (BSC 2004e, Section 6.12).

Seepage monitoring was also conducted in the ESF at the ECRB Cross-Drift crossover. Figure 5-16 illustrates the general layout of the crossover point of the ECRB Cross-Drift with the main drift. The purpose was to determine if water used during the ECRB Cross-Drift excavation migrated down to the crown of the underlying ESF and produced seepage. Moisture monitoring in the ventilated portion of the ECRB Cross-Drift gathered data on the drying impacts of the ESF ventilation (BSC 2004e, Section 6.10).

Additional studies included the installation of bulkheads to isolate sections of the ECRB Cross-Drift, as well as other alcoves and niches. The purpose was to see if natural seepage could be observed under ambient conditions, without the disruptive effects of tunnel ventilation. Sensors, containers to capture drips from rock bolts, and a remote camera viewing capability were installed in the ECRB Cross-Drift. Moisture was observed in the ECRB Cross-Drift. Collection and analysis of in situ measurements and water samples from the bulkhead sections of the ECRB Cross-Drift were used to determine if the source of the water was condensation or seepage (BSC 2004e, Section 6.10).

Infiltration—These studies collected information to characterize the infiltration-related parameters and soil and rock hydrologic properties that control the present-day natural infiltration processes and net-infiltration rates.

A network of neutron boreholes (a total of 99 boreholes) was used to gather data on precipitation infiltration into soils and bedrock at different geomorphologic areas throughout the Yucca Mountain region. A map was produced documenting the distribution and thickness of surface deposits on and around Yucca Mountain (SNL 2008a, Section 6.5.2). Various laboratory and field techniques were used to estimate soil properties and root zone parameters based on analogue data and the soil mapping discussed above. Ring infiltrometer tests were used to establish the rate at which water infiltrates into stream and valley fill deposits (SNL 2008a).

Six small watersheds that drain from Yucca Mountain were instrumented to record run-on/runoff events in response to precipitation. Establishment of evapotranspiration measuring sites was used to provide the means for estimating the amount of water lost to evapotranspiration (and not available as net infiltration). In addition, these results were correlated to vegetation type and species density per acre, resulting in accurate estimates of discharge or recharge within both the subbasins and the regional groundwater system (SNL 2008a, Appendix B).

5.1.5.3 Thermal Testing and Near Field Geochemical Characteristics

Geochemistry studies were used to characterize site geochemical conditions. The near field is the volume of rock that surrounds the emplacement drifts, and is that part of the natural system that is likely to experience potential changes to hydrologic, mineralogical, chemical, or mechanical characteristics caused by heating of the repository block. Geochemical processes are expected to be dominated by fluid-rock interactions and reactive transport. The fluid-rock interactions between hydrologic and geochemical processes were investigated. The studies evaluated the baseline geochemical and mechanical nature of the repository horizon, and through thermal tests investigated changes to those characteristics that would occur during and after the thermal period. Samples were obtained from surface locations, boreholes, and the underground facilities. See Figures 5-2, 5-3, 5-6, 5-8, and 5-10 for exploration locations.

The Large Block Test was a controlled, one-dimensionally-heated thermal test, using a 3 m × 3 m × 4.5 m block of Topopah Spring Tuff located on the eastern flank of Fran Ridge (Figure 5-13 shows the location on Fran Ridge). The block was characterized and instrumented, and the sides were sealed and insulated to inhibit moisture and heat loss. The temperature on the top of the block was also controlled. The block was heated for 13 months, during which time temperature, moisture distribution, and deformation were monitored. After the block cooled, a series of boreholes were drilled and one of the heater holes was over-cored to collect samples for post-test characterization of mineralogy and mechanical properties. The test provided the initial field results to assess instrumentation for thermal and mechanical measurements, and to assess survivability and migration of microbes (SNL 2007d, Section 6.1).

The Single Heater Test observed and quantified thermally-driven, coupled hydrologic, chemical, and mechanical responses of the rock mass in a moderate-scale field test in Alcove 5 (see Figure 5-8 for the test location in the ESF). Figure 5-17 is a schematic layout of the test bed. The test allowed for observation of coupled processes and changes in a 700 cubic meter block during 9 months of heating (followed by 9 months of cooling) of the rock mass surrounding a single rod heater. Three vertical faces of the block were exposed and available for direct observation. In addition to investigating properties at an intermediate scale, the various instrumentation types that were installed provided an assessment of their use in larger-scale thermal testing in the adjacent Drift Scale Test (SNL 2007d, Section 6.1).

The Drift Scale Test observed and quantified the thermally-driven, coupled hydrologic, chemical, and mechanical processes in the rock mass of a large scale field test. The test allowed for observation of coupled processes, and measurement of changes at a large-scale during 4 years of heating (followed by 4 years of cooling) of the rock mass surrounding a drift (47.5 m long and 5 m diameter) in Alcove 5 (See Figure 5-8 for location in ESF). Figure 5-18 shows a schematic layout of the test bed. Figure 5-19 presents a schematic of the relationship of boreholes and instrumentation relative to the heated drift, the access/observation drift, and connecting drift. The heat source consisted of 9 in-drift canister heaters and 50 additional wing heaters that were located in boreholes all along both sides of the drift (SNL 2007d).

Investigations to support potential in-drift processes were conducted to determine coupled processes that could lead to geochemical-driven reactions that would change seepage chemistry, and which would then interact with the engineered barrier components. These included evaluation of the relative humidity-temperature relationships for the onset of aqueous film formations. Deliquescence studies were conducted that investigated relationships for the onset of aqueous film formations in the presence of ionic salts and dusts. Evaporative concentration studies determined changes in concentrated solutions on heated metal surfaces. Microbial effects are addressed in the evaluation of Alloy 22 corrosion (SNL 2007e, Section 6.4).

5.1.5.4 Geotechnical Properties

Geotechnical studies were designed to provide information necessary for understanding both the preclosure and postclosure periods. These studies characterized geotechnical properties that could impact both proposed surface and subsurface repository structures, systems, or components considered to be important to safety until permanent closure is achieved, as well as those required for exercising the retrieval option. The postclosure needs were predicated on performance and design requirements to investigate and provide data that could be used to evaluate the probabilities and effects of nominal performance absent an initiating event, as well as the probability and effects caused by initiating events that might alter existing conditions at Yucca Mountain and adversely affect repository performance. Figure 5-6 shows the locations of surface investigations related to surface geotechnical evaluations.

Underground Facilities—Information was gathered from surveying, sampling, and testing of the ESF and ECRB Cross-Drift tunnels, as well as from tunnel boring machine pressure and mining rates. Tunnel convergence monitoring was conducted in the ESF to provide confidence in predictions of stability of the repository underground facilities over their 100 year (or longer) operational life.

The types of tests and other field activities performed to enhance understanding of rock mass behavior and in situ performance of ground control hardware installed to maintain the safety and stability of underground excavations included the following (BSC 2007a, Section 6.6.1):

- Single Heater Test
- Drift Scale Test
- Rock Mass Mechanical Field Tests:
  - Borehole Jack Tests
  - Plate Loading Test
  - In Situ Slot Tests
- ESF Ground Support Confirmation

- ESF Deformation Monitoring
- Steel Sets Monitoring.

For nonlithophysal rock, the lithostratigraphic contacts and fracture geometries from tunnels, boreholes, and outcrops were mapped. Rock quality data was collected for rock classification purposes, and limited index testing was performed across the site. The shape, size, and abundance of lithophysae, spots, and rims in repository lithophysal rock were mapped. This mapping was carried out along the ESF and ECRB Cross-Drift tunnels, in existing site boreholes, and where representative rock units outcropped (BSC 2007a, Sections 6.3.1.4 and 6.3.2).

Geophysical logging of boreholes was done to indirectly determine the vertical variation of bulk density and porosity data for lithostratigraphic zones. Laboratory thermal-mechanical tests were performed on intact small cores of nonlithophysal rock, and on other rock units from outside the repository horizon. Additional analyses included estimates of fracture shear constitutive behavior. The data on fracture shear response was augmented by conducting laboratory direct shear tests on large and small samples of nonlithophysal rock by joint set (BSC 2007a).

Tests of large diameter core samples of lithophysal rock included laboratory thermal-mechanical testing. These tests acquired information regarding porosity and size effects, but also provided input to calibrate the numerical simulations of mechanical lithophysal rock behavior (BSC 2007a, Section 6.3.2).

In situ site-specific rock behavior was investigated using small-scale borehole testing of thermal and mechanical behaviors, meter-scale mechanical and thermal testing of rock blocks, and drift-scale tests in both nonlithophysal and lithophysal rock. Long-term mechanical loading tests of meter-scale rock were conducted (BSC 2007a, Section 6.3.3).

Surface Facilities—Geologic, seismic, and geophysical data were obtained from 16 boreholes. Studies in western Midway Valley for design of the repository surface facilities have provided the data used to develop site-specific seismic design response spectra and time history for defining seismic design input ground motions. Geologic data, in-place density measurements, and laboratory evaluations were made on the alluvium encountered in test pits (Figure 5-6). Resonant column and torsional shear test results were measured for samples of tuff, alluvium, and engineered fill (BSC 2002a, Section 6.2). In conjunction with lithostratigraphic and structural data collected from surface-based boreholes, surface wave surveys have been used to determine the thickness of alluvial materials and the locations and directions of movement on faults and fault splays (BSC 2002a, pp. 231, 241, 249, 284, and 292). Figure 5-6 shows the locations of surface investigations related to surface geotechnical evaluations. Investigations to support detailed design that are also included on this figure are summarized in Section 5.1.6.4.

Geotechnical laboratory data that were acquired in 2000 and 2001 on a composite sample from the Fran Ridge borrow area included maximum and minimum density, compaction characteristics, specific gravity, particle-size distribution, static drained shear strength, and resonant column and torsional shear test results (this includes the same types of data as for the Waste Handling Building area test) (BSC 2002a, Section 6.5).

5.1.5.5 Meteorology and Climatology

These investigations collected hydrometeorological data as part of the climate and infiltration studies, and as input to the design program. These studies also provided data for the evaluation of potential airborne releases from the repository during the operational period. The various studies monitored local and regional meteorological conditions, evaluated atmospheric and meteorological phenomena at potential locations of surface facilities, identified and described extreme weather phenomena and recurrence intervals, and provided meteorology data (including average and extreme climatic phenomena). See Sections 5.1.5.6 and 5.2.6 for discussions of the Biosphere.

Meteorology—In 1985, Yucca Mountain Project weather stations were established to gather data on various weather parameters needed to characterize current local weather. Data collection included temperature, barometric pressure, humidity, wind direction, wind speed, cloud cover, rainfall amount, duration, and intensity (SNL 2008a, Section 6.5). Figure 5-20 shows the meteorological stations. Tipping bucket rain gages were added to the network, and supplemented by storage gages that were used to measure rainfall in the Yucca Mountain area at gage stations located throughout the site and surrounding region, resulting in precipitation results under present-day climate conditions. In addition, the Nevada Test Site meteorological data provided records going back to the 1950s. Regional weather stations, going back to the early 1900s, were used to supplement site-specific results and to understand the local and regional weather cycles.

Climate—Studies were conducted to provide data for present-day and future climate evaluation. Dating of the Devils Hole calcite provided a framework for correlation of the calcite record with past climates. Analysis of the Owens Lake ostracod record established the relationship between the species of ostracod present in the fossil records and climate. The SPECMAP deep-sea drilling records, and other global climate information, were used to establish a correlation between the Devils Hole record and the Owens Lake record (BSC 2004g, Section 6). Figure 5-21 shows the localities important to past and future climate estimates in the Yucca Mountain Region. Figure 5-22 shows present day stations that were used as future climate analogues.

Packrat midden analysis and dating was used to characterize the past regional climate by analyzing the remains of fossil packrat habitats, and by determining the types of plants present in the preserved middens (BSC 2004g, Section 6.5.1). Field surveys of recognized paleo-discharge sites in southern Nevada investigated their timing and water table elevation during active discharge. Precipitation and temperature records from analogue sites and ice cores established a link between measurements of modern precipitation and past environments that supported similar assemblages of plants, trees, and animals (BSC 2004g, Section 6.5.1).

Examination of the Earth orbital parameters was used to establish a relationship between the Earth orbital parameters and the cyclic behavior of global and regional climate (BSC 2004g, Section 6).

5.1.5.6 Reference Biosphere

The biosphere is defined as the total ecosystem, including the organisms inhabiting it and the abiotic factors, such as climate, soil, surface waters, and air. The reference biosphere refers to a representation of the environment inhabited by a hypothetical receptor, the reasonably maximally exposed individual (RMEI), where that receptor is exposed to radionuclides released from the repository. The present-day characteristics of the Amargosa Valley area are used to describe the reference biosphere and the pathways by which radionuclides released into the environment would reach the RMEI. The present-day characteristics of the Amargosa Valley population are also used to describe the RMEI. (SNL 2007f).

In addition to the meteorology and climatology results described above, air quality was estimated from analogue sites based on data in the U.S. Environmental Protection Agency AIRS data, and supplemented by onsite data collection. This provided site-specific data for dust loads. These loads were characterized using standard U.S. Environmental Protection Agency methods for inhalable and total dust loads.

Focused surveys assessed the consumption of locally produced foods and well water in the vicinity of Yucca Mountain. Food consumption was also evaluated based upon the United States Department of Agriculture Survey of Food Intake, using the amount of various food types consumed per year in the western U.S. (DOE 1997, Section 2.3).

Population density and distribution data were obtained from scientific investigations conducted in support of the Radiological Monitoring Program (BSC 2003, Section 5.0). Figure 5-23 illustrates the general population distribution near the site in Amargosa Valley. Employment, commute time, and other population data were obtained from the U.S. Census Bureau (Bureau of Census 2002).

Socioeconomic surveys conducted in the vicinity of Yucca Mountain investigated economic, demographic and agricultural (crops and livestock) characteristics of the area (CRWMS M&O 1997a; CRWMS M&O 1998a; and YMP 1999).

Farming practices, as reported by Amargosa Valley residents (Horak, C. and Carns, D. 1997. *Amargosa Focus Group Report*. Biosphere Study. Las Vegas, Nevada: University of Nevada, Las Vegas), and documented by the Cooperative Extension Service and the U.S. Department of Agriculture, were used to determine crop types, planting dates, and gardening practices in the Amargosa Valley (Mills et al.). Soil types were determined based on the United States Department of Agriculture Soil Survey (USDA 2004).

5.1.6 Testing and Monitoring Activities Conducted After the Conclusion of Site Characterization

Following the formal site designation in July 2002, and the completion of the site characterization phase of the work, a series of testing and monitoring activities were conducted. These activities included the following:

- Testing that could provide incremental improvements to data and models that form the technical basis for the license application (e.g., continuation of unsaturated zone seepage and transport investigations, and ECRB Cross-Drift unsaturated zone investigations.

- Supplemental information collection to increase confidence in the description of igneous activity in the Yucca Mountain region since conclusion of the first probabilistic volcanic hazard analysis (PVHA). Continued investigations focused on high resolution aeromagnetic data that indicated anomalies that were interpreted to be buried basaltic volcanic features, drilling data, Ar/Ar and K/Ar dates on surface and buried basalts, and geochemical and trace element data on surface and buried basalts. The results of these continuing investigations are found in SAR Section 2.3.11.2.

- Testing and monitoring to extend and support performance confirmation and the information baseline. These additional investigations supported enhanced analyses in response to (1) the programmatic and regulatory changes that drove modification of the TSPA; and (2) the addition of a new proposed period of regulatory concern.

- Testing to support detailed design (e.g., additional subsurface detailed mapping and geotechnical investigations for preclosure facilities beyond what was necessary for characterization).

- Continuation of long duration elective testing activities to advance the understanding of related processes, and reduce conservatism in some models. These elective activities (e.g., cool down of the Drift Scale Test, continuation of the Long Term Corrosion Test Facility, and waste form testing) began during the site characterization period, but were not necessary to complete for site selection/recommendation.

- Utilization of external sources (e.g., affected units of government oversight, Nevada System of Higher Education cooperative agreements, and other federal, state, and local government regulatory and long-term monitoring programs) to provide increased confidence in the technical program.

After the completion of site characterization, information from these internal and external sources continued to be evaluated in conjunction with ongoing testing and monitoring results. Sections 5.1.6.1 through 5.1.6.6 provide brief descriptions of these testing and monitoring activities. Results from these activities are presented in Section 5.2.

5.1.6.1 Geology

Subsurface Characterization—Subsurface mapping within the ESF and ECRB Cross-Drift after the site characterization phase of the work included further detailed mapping of fractures, faults, stratigraphic contacts, and lithophysal characteristics to support design. Results from this effort were used for the *Subsurface Geotechnical Parameters Report* (BSC 2007a, Section 6.4) and the *Drift Degradation Analysis* (BSC 2004h, Section 6.1). Additional mapping and data analysis was continued under cooperative agreements (e.g., in support of the Nye County Early Warning System monitoring wells). In addition, the hydrogeologic framework model used to support the saturated zone models was updated (SNL 2007g, Section 6.4) by incorporating Nye County Early Warning Drilling Program data through Phase IV. The well logs aided in enhancement of stratigraphic cross sections as new subsurface stratigraphic information became available. The data and interpretations from this activity are generated from the southern-most area of the postclosure controlled area, and only apply to the saturated zone models.

Geophysical Surveys—Regional and high resolution aeromagnetic surveys were flown to investigate buried geologic structures (including buried volcanic centers). Figure 5-24 shows the outline of the area surveyed and the boreholes that were drilled for confirmation of identified anomalies. Detailed ground magnetic and gravity surveys over suspected buried basaltic centers were conducted in order to characterize anomalies in appropriate detail for borehole siting.

Seismicity Monitoring—A network of seismometers is maintained by the University of Nevada Reno through cooperative agreement with the DOE. The network consists of seismometers located on the surface (near the repository) and in the underground tunnel complex, which since 2007 is a single underground monitoring site in Alcove 5.

5.1.6.2 Hydrology

Unsaturated zone testing and monitoring activities that were conducted after site characterization and are now completed included long-duration elective testing activities that were not necessary to complete for site characterization. These multiyear field testing activities for evaluating unsaturated zone properties were completed in 2006 (BSC 2006a, Section 6.0). These activities advanced a fundamental understanding of some processes, added to the performance confirmation baseline, and reduced conservatism in some models.

Unsaturated zone testing and data collection continued in test beds and at the ESF and ECRB Cross-Drift as continuations of ongoing science. Unsaturated zone testing areas included a portion of the ECRB Cross-Drift tunnel that was isolated by bulkheads; this section was instrumented to evaluate seepage and moisture conditions. Alcove 8–Niche 3 testing was also conducted as part of ongoing corroborative investigations. These tests collected data on fracture flow characteristics in the upper lithophysal and middle nonlithophysal subunits.

A seepage event was observed in the South Ramp of the ESF in February 2005. The analysis of this event (Finsterle and Seol 2006) was completed in May 2006. The analysis indicated that the approach for estimating seepage at the repository horizon—developed for the seepage model for performance assessment (BSC 2004i) and the seepage abstraction model (SNL 2007h)—gives reasonable seepage predictions even when applied to the South Ramp of the ESF, which is in a different hydrogeologic unit and conditions.

The USGS continued to monitor the stage (water level) and discharge of lakes and streams at a network of surface-water stations and sites in the vicinity of Yucca Mountain, using standard USGS methods (Figures 5-9 and 5-25).

Saturated zone monitoring data collection continued in selected wells located near Yucca Mountain, as part of the oversight by Nye County, and as part of a cooperative agreement with the Nevada System of Higher Education (Figure 5-26). These ongoing activities include monitoring, sampling, and analyzing saturated zone water from Nye County and site wells. Information from the Nye County program was used to update the saturated zone site-scale flow model (SNL 2007b). The data include new stratigraphic and water level data from Nye County wells, single- and multiple-well hydraulic testing data (SNL 2007a), and new hydrochemistry data (SNL 2007b, Section 1).

Saturated zone alluvium testing activities continued at the Alluvial Test Complex (Figure 5-27), and other Nye County wells, to evaluate the hydraulic properties of the saturated alluvium zone. This testing was performed by Nye County in cooperation with Project scientists, using multiple wells south of Yucca Mountain.

At the Nye County 22 site (Figure 5-27), cross-hole hydraulic tests were conducted in 2003 to determine the transmissivity, hydraulic conductivity, and storativity in four separate intervals in the saturated alluvium. Two single-hole injection-pumpback tracer tests, with 3-day and 4-week drift periods for the injected tracer plume, were conducted in 2004, and two cross-hole tracer tests in two orthogonal directions were conducted in 2005 to determine flow porosity and longitudinal dispersivity of the alluvium at the site. In October 2006, a natural gradient tracer test was initiated from north to south along the presumed natural gradient between two wells at the Nye County 22 site, 20 m apart. Breakthrough occurred in March 2007, 141 days after tracer injection.

5.1.6.3 Thermal Testing and Near Field Geochemical Characteristics

Data collection and analysis continued during the cooldown phase of the Drift Scale Test beyond Site Recommendation. These data are compiled and evaluated together with earlier information collected from the Drift Scale Test, as well as the Large Block Test and Single Heater Test in the *Thermal Testing Measurements Report* (SNL 2007d). In addition, in-depth investigations were conducted after Site Recommendation to evaluate (1) heat and mass loss through the Drift Scale Test bulkhead; (2) investigation of Drift Scale Test water samples with elevated concentrations of fluoride and chloride; and (3) discoloration of a canister (SNL 2007d). Results of thermal testing are included in SAR Section 2.3.6.

The Drift Scale Test cooling phase started January 14, 2002, and lasted through December 31, 2005. After the planned cooling phase was completed, limited measurements of a few selected sensor locations were continued to assess a return to ambient conditions. The Drift Scale Test continued during the post-2002 cooling phase, with emphasis on the dissolved ion chemistry of water as it moved back into the dryout zone. This testing included activities necessary for both the passive monitoring and active testing associated with the Drift Scale Test.

In addition to monitoring and analysis of data collected during the cooling phase of the Drift Scale Test discussed above, other investigations into Near Field processes included thermal testing in the ECRB Cross-Drift (i.e., single borehole heater tests), dust sampling, chemical analyses of bulk dust and water soluble components, geochemical characterization of the host rock as a dust source, dust deliquescence experiments, isotopic studies of secondary minerals in the unsaturated zone to characterize long-term percolation rates associated with climate change, isotopic and geochemical studies of zeolitized rock to evaluate radionuclide retardation capability of subrepository units, and chemical and isotopic analyses of pore water. The results of geochemical investigations as they apply to evaporation are summarized in the *In-Drift Precipitates/Salts Model* (SNL 2007i).

5.1.6.4 Geotechnical Properties

Additional data collection and analysis of geotechnical properties continued after site characterization to support design. This resulted in five design related reports: (1) a seismic model input report that summarizes the seismic-related testing and results (BSC 2004j); (2) a soils geotechnical report (BSC 2002a); (3) another soils geotechnical report (BSC 2008b); (4) a report on subsurface geotechnical properties (BSC 2007a); and (5) a geotechnical data report (SNL 2008b).

5.1.6.5 Meteorology and Climatology

There has been ongoing collection of meteorological data at Yucca Mountain since 1985. This activity has continued as part of post–site characterization, and is expected to continue during the licensing process.

A numerical analysis was conducted to identify, extract, and reformat weather (meteorological) data that are appropriate for use as inputs to an infiltration model within the Yucca Mountain region (SNL 2006). The analysis used current meteorological data (e.g., precipitation and temperature) from source stations and converted the data into a form suitable for the generation of meteorological conditions for predicted future climates in the Yucca Mountain region over the next 10,000 years. In addition, a new report on *Local Meteorology of Yucca Mountain, Nevada, 1994–2006* (BSC 2007c) was developed to (1) describe the Yucca Mountain Project meteorological monitoring program; and (2) provide summaries of temperature, precipitation, and wind features (e.g., direction, speed, and gusts) that characterize the Yucca Mountain area. This report summarizes data collected from 1994 through 2006, and is intended for use as a source of local meteorological information.

5.1.6.6 Air Mass Loading

Airborne mass loading measurements were supplied by the Desert Research Institute in Amargosa Valley. Model results were validated using alternative models and relevant published literature sources as described in the *Biosphere Model Report* (SNL 2007f, Section 7.1.2). Results of modeling are discussed in SAR Section 2.3.10.6.

5.2 SUMMARY OF SITE CHARACTERIZATION RESULTS

[NUREG-1804, Section 1.5.3: AC 2]

Results of site characterization testing and model development are applied in screening the FEPs to be included in the TSPA, as well as the justifications for FEP exclusion, as summarized in SAR Section 2.2. Process and abstraction models developed to support the TSPA are described in SAR Sections 2.3.1 to 2.3.11, and the TSPA is described in SAR Section 2.4.

This section provides brief descriptions of the geology, hydrology, geochemistry, geotechnical properties, climatology and meteorology and other environmental factors, and the reference biosphere. Site features, events, and processes that could affect repository safety are reviewed, and the principal results from the site characterization program and post–site characterization activities are also summarized for each topical area.

5.2.1 Overview of the Geology of the Yucca Mountain Site

This section describes the geology of the Yucca Mountain site and region, including the stratigraphy of the site and region, and discusses the origin of the various rock units. The structural framework, including the locations and characteristics of faults and fractures, is also summarized. An overview of the tectonic setting is provided to establish a context for discussions of the seismicity and volcanism in the site area. The attributes of the geology that are relevant to estimating postclosure performance are summarized, followed by an overview of the geologic hazards that must be considered during construction and operation of the repository.

5.2.1.1 Physical Setting of the Repository Site

Yucca Mountain is located in the north-central part of the Basin and Range Physiographic Province, commonly referred to as the Great Basin (Figure 5-28). The mountain ranges of the Great Basin are mostly tilted, fault-bounded blocks more than 80 km in length. They are generally 8 to 24 km wide, rise from 300 m to more than 1,500 m above the floor of intervening basins, and occupy approximately 40% to 50% of the total land area. The deep structural depressions forming the basins contain alluvial sediments of late Tertiary and Quaternary ages, ranging in thickness from a few hundred meters to more than 3 km. Within this landscape, erosional processes are concentrated in the high, steep, uplands, whereas deposition and depositional processes are generally concentrated in the relatively arid lowlands (BSC 2004a, Section 2.1).

Yucca Mountain is an irregularly shaped upland area, 3 to 8 km wide and about 35 km long. The crest of the mountain reaches elevations of 1,500 to 1,930 m, or about 125 to 275 m higher than the floor of adjacent washes and lowlands (BSC 2004a, Section 3.2.1.1). The north-trending pattern of ridges and valleys that characterize the uplands of the Yucca Mountain area is bounded by high-angle normal faults with vertical displacements ranging from a few meters to a few hundred meters. Yucca Mountain is composed of fine-grained volcanic rocks that are tilted toward the east. Fault-bounded west-facing slopes are generally high, steep, and straight, in contrast to the more gentle and commonly deeply dissected east-facing slopes (BSC 2004a, Section 3.2.1.1).

5.2.1.2 Stratigraphy

Yucca Mountain consists of successive layers of volcanic tuffs, which were formed approximately 14 to 11.5 million years ago by eruptions of volcanic ash from calderas to the north (BSC 2004a, Sections 3.2 and 3.3). Late-Tertiary volcanic rocks dominate the exposed and near-subsurface stratigraphic sequence at Yucca Mountain. These rocks consist mostly of pyroclastic flow (ash flow) and fallout tephra deposits with minor lava flows and reworked materials. At Yucca Mountain and in the surrounding area, Cenozoic rocks overlie complexly deformed Paleozoic and Precambrian rocks along an erosional unconformity. Cenozoic rocks of the Yucca Mountain region fall into three general groups: (1) pre–Middle Miocene sedimentary (including volcaniclastic) rocks that predate creation of the southwestern Nevada volcanic field; (2) the Middle to Late Miocene volcanic suite that constitutes the southwestern Nevada volcanic field; and (3) the Plio-Pleistocene basalts and basin-fill sediments (Figure 5-29).

The physical properties of the tuff and lava units that make up Yucca Mountain often show great contrasts across depositional contacts, and some contrasts within units, but tend to be relatively uniform laterally over broad areas. These characteristics are due to the following factors:

- Rapid deposition of large batches of homogenized material over large areas as ash flows
- Differences in the composition of each eruptive batch (and sometimes differences in the composition of first-erupted and last-erupted material in a single eruptive batch)
- Differences in postdepositional processes of welding, vapor phase crystallization, alteration, and gas dispersion.

Welded tuffs result from ash that was compressed and fused under high-temperature conditions; nonwelded tuffs form at lower temperatures, are less dense and brittle, and have a higher porosity. These differences in rock properties, mineralogy, and geochemistry have been used as characteristics or criteria to develop a detailed stratigraphic subdivision of the major lithostratigraphic units (BSC 2004a, Section 3.3). A generalized stratigraphic column of the Tertiary volcanic rocks in the vicinity of Yucca Mountain is illustrated in Table 5-3 (Stuckless and Levich 2007, Table 1, pp. 60 to 61). Some of the upper units are not present within the repository block. Figure 5-30 correlates those units in the immediate vicinity of the Yucca Mountain repository. Figure 5-31 illustrates the stratigraphic column at Yucca Mountain, showing detail for the repository host horizon.

Most of the surface of Yucca Mountain is composed of the volcanic rocks of the Paintbrush Group (about 12.7 to 12.8 million years old), which consists of four lithostratigraphic units, each primarily composed of pyroclastic flow deposits interstratified with small-volume pyroclastic flow and fallout tephra deposits. Figure 5-32 illustrates a generalized map of geologic units present at the surface in the vicinity of Yucca Mountain, whereas Figure 5-33 shows a geologic section across Yucca Mountain. In descending order, specifically on Yucca Mountain in the area of the repository footprint, these units are the Tiva Canyon, Yucca Mountain, Pah Canyon, and Topopah Spring tuffs. Figure 5-30 provides a comparison of various nomenclatures used to represent the rock units at Yucca Mountain. The Paintbrush Group is one of the most widespread and voluminous caldera-related assemblages in the southwestern Nevada volcanic field. The Yucca Mountain and Pah Canyon tuffs are volumetrically minor, but are of potential hydrologic importance because of their high matrix porosity compared to the Tiva Canyon and Topopah Spring tuffs. The Paintbrush Group is dominated volumetrically by the Topopah Spring and Tiva Canyon tuffs. The Topopah Spring Tuff forms the host rock for the repository. Contacts of several lithostratigraphic units correspond with hydrogeologic and thermal-mechanical unit boundaries (Figure 5-30) throughout Yucca Mountain, and have been used in the development of three-dimensional geologic and hydrogeologic models (BSC 2004a, Section 3.3).

The Topopah Spring Tuff lithostratigraphic unit has a maximum thickness of about 380 m in the Yucca Mountain vicinity, and is divided into a lower crystal-poor rhyolitic member (Tptp) and an upper crystal-rich quartz-latitic member (Tptr). Each member is divided into numerous zones, subzones, and intervals, based on variations in characteristics such as lithophysal content, crystal content and assemblage, size and abundance of pumice and lithic clasts, distribution of welding and crystallization zones, and fracture characteristics (Figure 5-30). The repository will be located in the densely welded and crystallized rocks in the crystal-poor member of the Topopah Spring Tuff. The four lithostratigraphic zones that comprise the repository horizon are the upper lithophysal (Tptpul), middle nonlithophysal (Tptpmn), lower lithophysal (Tptpll), and lower nonlithophysal (Tptpln) zones (BSC 2004a, Section 3.3), as shown in Figure 5-30.

Beneath the Paintbrush Group, the Calico Hills Formation (12.9 million years old) is a complex series of rhyolite tuffs and lavas. Five pyroclastic units, overlying a bedded-tuff unit and a locally occurring basal sandstone unit, are present in the Yucca Mountain area. The formation thins southward from thicknesses of as much as 457 m. The unit outcrops in the northern part of the site area; its type section is in the Calico Hills to the east of Yucca Mountain (BSC 2004a, Section 3.3.4.6).

The Crater Flat Group, which is located stratigraphically below the Calico Hills Formation, consists of three lithostratigraphic units with large-volume pyroclastic flow deposits and interstratified bedded tuffs. In descending order, these lithostratigraphic units are the Prow Pass, Bullfrog, and Tram tuffs, ranging in age from 13.1 to 13.5 million years (BSC 2004a, Section 3.3.4.5).

Depositional History—Tuff units of the Crater Flat Group, the Calico Hills Formation, the Paintbrush Group, and the Timber Mountain Group are widely distributed in the southwestern Nevada volcanic field. At least six major calderas erupted between about 15 and 7.5 million years ago, creating volcanic features in the surrounding area (BSC 2004a, Section 2.3.5.1).

Peak volcanism in the southwestern Nevada volcanic field occurred during eruption of the Paintbrush and Timber Mountain groups, when more than 4,500 km^3 of silicic magma were erupted in two episodes separated by a span of about 1 million years. The two major units of the Timber Mountain Group, the Rainier Mesa Tuff (11.6 million years ago), and the Ammonia Tanks Tuff (11.4 million years ago) are extensively distributed within the western half of Crater Flat basin, but outcrops are sparse at Yucca Mountain (BSC 2004a, Section 2.3.5.1).

In the Yucca Mountain region, basaltic volcanism reflects the generation of small, discrete batches of basaltic magma at upper mantle depths (60 km) capable of making their way quickly to the surface. In Crater Flat, west of Yucca Mountain, the oldest basalts encountered in boreholes are dated at about 11.3 million years (Figures 5-29 and 5-34). However, no further basaltic volcanism occurred in Crater Flat until 3.7 million years ago, when a group of five northwest-aligned scoria cones and lava flows were emplaced in southeastern Crater Flat. This latter episode represents the largest volume of basaltic volcanism in Crater Flat. Following the episode 3.7 million years ago, a basaltic eruption episode occurred at approximately 1 million years ago. It consisted of four cinder cones (Little Cones, Red Cone, Black Cone, and Makani Cone) aligned along a north-northeast trend across Crater Flat. Most of the volume from this episode is associated with Red Cone and Black Cone. The most recent episode of basaltic volcanism created the Lathrop Wells Cone complex, which includes fissure eruptions, spatter and scoria cones, and aa basalt. The Lathrop Wells Cone complex is about 80,000 years old (BSC 2004c, Section 6.1).

Quaternary deposition in the Yucca Mountain geologic setting (apart from the sporadic and volumetrically minor basaltic volcanism discussed above) is chiefly restricted to alluvial basin deposition. In many basins, alluvial deposition was a continuation of sediment infilling that was underway in latest Miocene and Pliocene time. Closed basins in the area received alluvial sediment hundreds of meters thick throughout the Plio-Pleistocene, in response to continuing faulting, subsidence, and range flank erosion (BSC 2004a, Section 2.3.5.2). The Quaternary landscape in the Yucca Mountain area reflects colluvial, eolian, and alluvial processes that have responded to varying climates and climatic changes. Distribution of Quaternary deposits also reflects the tectonic environment of the area, as expressed in the topography of the mountain and adjacent basins (BSC 2004a, Section 3.3.7.5).

5.2.1.3 Structural Framework

The structural framework of Yucca Mountain and the surrounding area is expressed by tectonic features of faults and fractures. Geologic mapping, borehole, and geophysical investigations provide information on the spatial and temporal patterns of faulting and fracturing of the Miocene-age volcanic bedrock at Yucca Mountain. Structural geologic data contribute to an evaluation of the volume and quality of rock available for underground construction of a repository, the delineation of hydrologic flow paths, and the assessment of ground motion and fault displacement hazards.

5.2.1.3.1 Faults

The dominant element of the structural framework of the site area consists of the major block-bounding faults. Block-bounding faults are spaced 1 to 5 km apart, and consist of separate large, fairly intact blocks of generally east-dipping volcanic strata. In the site area (Figure 5-34), these faults include (from west to east) the Windy Wash, Fatigue Wash, Solitario Canyon, Bow Ridge, and Paintbrush Canyon faults. Faults generally dip 50° to 80° to the west (BSC 2004a, Section 3.5.3). Figure 5-35 illustrates the known or suspected Quaternary faults in the region.

Within structural blocks, small strains are accommodated along intrablock faults. The Ghost Dance Fault is a prominent intrablock fault at Yucca Mountain. Intrablock faults may represent small structural adjustments in response to displacements along the block-bounding faults (BSC 2004a, Section 3.5.4.3).

5.2.1.3.2 Fractures

Fractures are located throughout the volcanic rocks at Yucca Mountain. Fracture orientation, length, smoothness, connectivity, and other attributes are variable and strongly dependent on stratigraphic position. The hazard from fractures and associated rockfall will be location-specific, depending on both the lithostratigraphic unit that an access tunnel or emplacement drift encounters and the orientation and size of the tunnel or drift in each lithostratigraphic unit. The hazard from fractures and rockfall under static conditions will be bounded or enveloped by the hazard from fractures and rockfall under seismic loading conditions. The rockfall hazard under seismic loading conditions is discussed in SAR Section 2.3.4.4.

Fractures in the welded units at Yucca Mountain can be divided into two groups: those associated with cooling processes, and those associated with tectonic processes. The first fractures to form were long, steeply dipping fractures associated with the cooling process. As cooling progressed, smaller, truncated fractures were formed, which are typically moderately to steeply dipping and commonly exhibit orientations similar to the longer, high-angle fractures. Tectonic features consisting of faults and shears formed last.

The lithophysal and nonlithophysal zones within the welded tuffs of the repository horizon exhibit distinctive fracturing patterns and characteristics. In general, the nonlithophysal units are hard, strong, fractured rocks with matrix porosities of 10% or less. Figure 5-36 schematically illustrates the structure of the Topopah Spring Tuff in the immediate vicinity of the repository horizon. SAR Table 2.3.4-6 provides the general characteristics of fractures in the middle nonlithophysal unit. Fractures that formed during the cooling process are the primary structural features in these units. In contrast, the lithophysal units have significantly fewer fractures, with trace lengths greater than 1 m, but the porosity of the lithophysal cavities is fairly uniform (BSC 2004h, Section 6.1.4).

Based on observations at the surface and in the ESF, the total width of a fault zone within the repository block (note that block bounding faults have larger disrupted areas) may include a zone of influence in which fracture properties are modified. These modifications may include a higher fracture intensity, or a change in some other parameter, such as fracture orientation. The width of the zone of influence is generally quite narrow, ranging from less than 1 m up to 10 m from the fault. Also, the width of the zone generally correlates with the amount of fault offset. The amount of deformation associated with faults is dependent, in part, upon the properties of the lithologic unit involved in the faulting. In comparison to brittle, welded rocks, nonwelded units accommodate a greater amount of extensional strain before failing by fracture (BSC 2004a, Section 3.5).

Lithology plays a role in the interaction between discontinuous faults and the fracture network. Because each lithostratigraphic zone at Yucca Mountain has characteristic fracture attributes, spacing, trace length, and joint type, each unit is unique in its ability to deform by distributed slip along fractures (BSC 2004a, Section 3.5.8). The result is that a discrete break in one lithostratigraphic unit may be a broad zone of distributed deformation in another. For example, individual faults in the Sundance Fault Zone and elsewhere at Yucca Mountain are vertically and laterally discontinuous. Two probable mechanisms are distributed brittle deformation, which is associated with diffuse breccia bodies, and minor offsets along numerous preexisting cooling joints (Potter et al. 1999, pp. 1, and 5 to 6).

5.2.1.4 Geotechnical Properties of Stratigraphic Units

The principal geotechnical properties of the soil and rock units that are important to the design of safety-related facilities are described in Section 5.2.4 and SAR Section 1.1.5.3. Explorations undertaken to assess these properties have included geologic mapping, drilling of boreholes, excavation of test pits and geologic trenches, and geophysical testing. In some cases, properties have been developed through simulations and numerical analysis. Geotechnical properties that are described are static properties, including strength and deformation characteristics; dynamic properties, as functions of shear strain; and thermal properties, including thermal conductivity and thermal expansion. A shear-wave velocity profile of the site was developed for use in the ground motion analysis.

5.2.1.5 Tectonic Setting

Yucca Mountain is located in the Walker Lane Domain portion of the Basin and Range Province, which is characterized by thin crust, basaltic volcanism, high topography, block and detachment faulting, and west-northwest extension (Thompson et al. 1989, p. 178; Zoback and Zoback 1989, p. 530) (Figure 5-37). The immediate area around Yucca Mountain is characterized by closely spaced, west-dipping, normal faults. Tectonic models for Yucca Mountain and its vicinity explain current geologic structure and geophysical data in light of regional tectonic processes, and are consistent with data at both regional and local scales (BSC 2004a, Section 4.1). Several tectonic models have been proposed for the Yucca Mountain vicinity, and these models were evaluated as part of both the probabilistic seismic and volcanic hazard analyses, described in Sections 5.2.1.5.2 and 5.2.1.5.3, respectively.

Tectonic deformation within the Basin and Range Province results from the interplay of boundary forces and internal buoyancy forces. The boundary forces are fundamentally related to the interaction of the Pacific Plate with the North American Plate. Internal to the plates, buoyancy forces exist because of local density contrasts and the high topographic elevation of the province. Geodetic and satellite GPS data indicate that the Pacific Plate is moving northwest, relative to the North American Plate interior. The San Andreas fault system along the plate boundary accounts for the majority of this differential motion; however, the remainder is distributed through the Inyo-Mono Domain and through the Walker Lane Domain, which includes Yucca Mountain (Bennett et al. 1999, p. 371; Thatcher et al. 1999, p. 1716). The existence of numerous precariously balanced rocks at Yucca Mountain is considered to indicate that strong-motion has not occurred for tens of thousands of years (Brune and Whitney 2000, Chapters A and M).

5.2.1.5.1 Geomorphic Processes and Erosion Rates

A wide variety of geologic evidence indicates that erosion at Yucca Mountain has occurred at very slow rates for the past several million years. Geomorphic observations of such tectonic features as volcanic cinder cones and fault scarps provide information on erosional and depositional processes. The kinds and rates of geomorphic processes have varied considerably during the Quaternary Period in response to the many cycles of climate change that took place. At present, semiarid conditions prevail in the southern Great Basin. During much of the Quaternary Period, however, cooler and wetter conditions existed; thus, most of the surficial deposits mapped on and around Yucca Mountain are the products of climatic conditions that were different from the present. Under the present climate, the landscape is dominated by warm temperatures and eolian processes, with infrequent storms producing localized runoff, whereas during cooler and wetter climates there were changes in the type and density of vegetation, increases in runoff and streamflow, and the potential for longer periods of freezing (BSC 2004a, Sections 3.2 and 3.4.4).

Quaternary displacement along block-bounding faults also influences depositional patterns on hill slopes and on the adjacent valley or basin floors. Slip rates on the local faults near Yucca Mountain are relatively low in comparison with slip rates for significant regional faults. Recurrence intervals, or return times, for earthquakes on the local faults are long. This low-faulting rate has resulted in subtle landforms and is reflected in the preservation of early and middle Pleistocene deposits on hill slopes, as well as the lack of well-defined alluvial fans at the base of the slopes. This characteristic results from the homogeneous nature of the underlying volcanic tuff at the ridge crest and from the low rates of uplift (BSC 2004a, Section 3.2.2.1).

Little erosional modification has taken place on the Lathrop Wells cinder cone, which is the youngest volcanic center in the Yucca Mountain region, with an estimated age of 80,000 years (Heizler et al. 1999, pp. 768 and 803). The four middle Quaternary (about 1 million years old) cinder cones in Crater Flat are fairly well preserved. In contrast, the original topography associated with the 3.7 million year old basaltic centers in central Crater Flat has been strongly modified by erosion and formation of deep gullies, channel networks, and soils characteristic of a long depositional history (Wells et al. 1990, p. 551).

A model representing geomorphic processes at Yucca Mountain (BSC 2004a, Section 3.4.5) shows that major erosion and deposition occur primarily during climatic transitions, with periods of more stable climate being times of relative landscape stability. The greater the magnitude of temperature and precipitation fluctuations during these transitions, the greater the landscape response.

5.2.1.5.2 Seismicity and Seismic Hazard

The assessment of seismic hazards at Yucca Mountain focuses on characterizing the potential ground motion and fault displacement that will be associated with earthquake activity in the vicinity of the site. Seismic hazards at Yucca Mountain are assessed probabilistically. The assessment is founded on the evaluation of a large database that incorporates information on all known seismic sources in the Yucca Mountain region, including their maximum earthquakes, source geometry, and earthquake recurrence. The data set contains information about prehistoric earthquakes on nearby Quaternary faults. The historical earthquake record and information on the attenuation of ground motion are also important components of this database. The seismic hazard assessment considers the patterns and amounts of fault displacement and explicitly incorporates uncertainties in the characterization of seismic sources, fault displacement, and ground motion (BSC 2004a, Section 4.3). The effects of seismic activity on the EBS are modeled and discussed in SAR Section 2.3.4.

Seismic hazard evaluations rely on a description of the temporal and spatial distribution of both prehistoric and historical earthquakes, their magnitudes, and how they relate to the seismotectonic processes of the region. The temporal and spatial occurrence of earthquakes for a given region is evaluated from two sources: historical (instrumental records and reported effects), and prehistorical (paleoseismic data) (BSC 2004a, Section 4.3).

The probabilistic seismic hazard assessment at Yucca Mountain is a function of earthquake magnitude, the rate of occurrence, and the distance of occurrence. Because earthquake ground motions attenuate with distance, the farther an earthquake occurs from Yucca Mountain, the larger it must be to contribute significantly to the hazard at the site. If distant earthquakes are infrequent, ground motions from closer events of similar or lesser size will be more significant to the probabilistic hazard at the site. Thus, as distance from Yucca Mountain increases, seismic hazard studies focus on the longer and more active faults (BSC 2004a, Section 4.3.1).

As part of the probabilistic seismic hazard analysis (PSHA), a catalog of historical earthquakes was compiled for the region within 300 km of the repository site at Yucca Mountain. When referring to earthquake magnitudes, the following scales are cited: M_L indicates Richter local, and M_w indicates moment magnitude. All known magnitudes are listed in the catalog. Figure 5-38 shows events in the catalog within 100 km with magnitudes greater than M_w 2.5 prior to 2000. The catalog includes recorded historical events of M_w 5.5 and larger within the 100 km radius around Yucca Mountain (BSC 2004a, Section 4.3.1.2).

While the southern portion of the Nevada Test Site, southeast of Yucca Mountain, is one of the more seismically active regions in the southern Great Basin, the immediate area beneath Yucca Mountain has a very low rate of seismicity. The zone of quiescence surrounding Yucca Mountain has been studied and is not an artifact of network design or detection capability. The "swarm" of small quakes in the northwest corner of the test site apparently is attributable to underground weapons testing in that area. Such tests can trigger minor "stress relief" quakes. Modeling of the strain field in southern Nevada suggests that this area is not accumulating significant strain, and that the Yucca Mountain area is an isolated block within the structural framework of the southern Great Basin (BSC 2004a, Section 4.3.1.5).

While the immediate Yucca Mountain area has been quiescent during this historical period, the paleoseismic evidence indicates active Quaternary faults exist near the site. Paleoseismic events exhibit very long times between events, and little or no microseismicity may occur on the faults during this long time period. Many faults in the Great Basin with paleoseismic evidence for prehistoric surface-rupture earthquakes have little or no associated historical seismicity (BSC 2004a, Section 4.3.1.5).

An analysis to bound credible horizontal peak ground motion velocities is provided in *Peak Ground Velocities for Seismic Events at Yucca Mountain, Nevada* (BSC 2005a). Rock testing data, geologic data, and ground-motion site response data were combined to determine a bounding horizontal peak ground velocity at Yucca Mountain. The bound to the horizontal PGV experienced at Yucca Mountain provides a reasonable bound to credible ground motions for TSPA (BSC 2005a).

5.2.1.5.2.1 Probabilistic Seismic Hazard Analysis Process

To assess the seismic hazards of vibratory ground motions and fault displacement at Yucca Mountain, a PSHA was performed. SAR Section 2.2.2.1 provides a comprehensive discussion of the PSHA, which provided quantitative hazard results both to support a postclosure performance assessment and to form the basis for developing seismic design criteria for the license application. The methodology is based on probabilistic analyses that incorporate a broad set of data on the behavior of faults, earthquake recurrence, and earthquake ground motion. The resulting PSHA for the Yucca Mountain site is state-of-the-practice. The PSHA explicitly incorporates and quantifies uncertainty due to both randomness and diversity of data interpretation, and presents this uncertainty in the final hazard results. Formal expert elicitation (SAR Section 5.4.2) was used to obtain interpretations of seismic sources and earthquake ground motion relationships that capture the range of interpretations that are supported by the data. The hazard analysis produces a distribution of hazard curves showing the annual probability with which various levels of ground motion or fault displacement are exceeded (CRWMS M&O 1998b, p. ES-1).

Two expert panels were convened for the PSHA, composed of individuals with a variety of institutional or organizational affiliations. Six teams of three experts each, who together formed a composite expertise in seismicity, tectonics, and geology of the Yucca Mountain region, developed seismic source characterizations. Seven individual experts made ground motion assessments. A deliberate process was followed in facilitating interactions among the experts, in training them to express their uncertainties, and in eliciting their interpretations. The experts' interpretations specifically incorporated uncertainties related to the data and to resolving alternative hypotheses and models (BSC 2004a, Section 4.3.4).

Three basic inputs are required for a PSHA (BSC 2004a, Section 4.3.4):

- Identification of relevant seismic sources and characterization of their source geometry
- Rate of earthquake occurrence for each seismic source and its magnitude distribution
- Attenuation relationships that provide for the estimation of a specified ground motion parameter as a function of magnitude; source-to-site distance; local site conditions; and, in some cases, seismic source characteristics (BSC 2004a, Section 4.3.4).

The analysis provides calculated annual probabilities that various measures of vibratory ground motion, such as peak horizontal acceleration, may be exceeded at the Yucca Mountain site. The seismic hazard curves that were produced represent the integration over all earthquake sources and magnitudes of the probability of future earthquake occurrence and, given an occurrence, its effect at the site. The methodology for evaluating fault-displacement hazards probabilistically is very similar to that for vibratory ground motions. Relationships for ground motion attenuation are replaced by relationships that describe the distribution, sense, and amounts of displacement with earthquake occurrence. Both primary and secondary fault displacements are addressed (BSC 2004a, Section 4.3). Several original approaches to characterize the fault-displacement potential were developed by the seismic source expert teams. These approaches were primarily based on empirical observations of the pattern of faulting at the site during past earthquakes, as determined from data collected during fault studies at Yucca Mountain. Empirical data were fed into appropriate statistical models for use by the experts (CRWMS M&O 1998b, Appendix H).

5.2.1.5.2.2 Probabilistic Seismic Hazard Analysis Results

The ground motion estimates and associated attenuation relationships were developed for a reference rock outcrop. This reference rock outcrop was defined to have geotechnical conditions identical to those at the depth of the buried repository, not those at the ground surface. The reference rock outcrop was used because, at the time the PSHA was conducted, limited site-specific data existed on the velocities and dynamic properties of the upper 300 m of rock and soil (BSC 2004j, ES, p. vi). For design analyses and analyses supporting the current performance assessment, additional site-specific data were available, and the effect on ground motion of the material between the waste emplacement level and the earth's surface (i.e., site response) was taken into account (BSC 2004a, Section 4.3).

Based on equally weighted inputs from the six seismic source expert teams and the seven ground motion experts, the probabilistic hazard for vibratory ground motion was calculated. Horizontal and vertical peak acceleration (defined at 100 Hz), spectral accelerations at various frequencies, and peak velocity were assessed and are expressed in terms of hazard curves. The hazard is also expressed in terms of uniform hazard spectra. The largest source of uncertainty in the hazard results is in the ground motion characterization (BSC 2004a, Section 4.3.4.2).

The probabilistic fault-displacement hazard was calculated for nine demonstration sites located at or near Yucca Mountain (CRWMS M&O 1998b, Section 4.3.4.2). Two of the sites were given characteristics to simulate locations within the ESF. The integrated results provide a representation of fault-displacement hazard and its uncertainty at the nine sites, based on the interpretations and parameters developed by the six seismic source expert teams. Separate results were obtained for each site in the form of summary hazard curves (BSC 2004a, Section 4.3.4.2).

5.2.1.5.3 Volcanism and Volcanic Hazard

The assessment of volcanism at Yucca Mountain builds on the knowledge of the late Tertiary and Quaternary history of igneous activity. As part of site characterization, investigations were performed to assess the ages and character of the volcanic episodes that have occurred in the region. Detailed field studies, including trenching and geologic mapping, as well as age determinations using multiple dating methods, have been conducted for volcanic centers in the Yucca Mountain region. A geochemical database exists for basalts of the Yucca Mountain region, which includes major elements, trace elements, and radiogenic isotopes. The levels of detail of the studies vary with the age of the volcanic activity. The most detailed studies are of the Pliocene and Quaternary (about 4 million years ago to the present) basaltic volcanic centers, because they record the most recent volcanic activity in the area and, therefore, provide valuable data for assessing the risk of future volcanism (BSC 2004a, Section 4.2).

5.2.1.5.3.1 Location of Basaltic Volcanism in the Yucca Mountain Region

Basalts were erupted in the Yucca Mountain region during two major episodes, beginning about 11.3 million years ago. Based on age and spatial groupings, the Quaternary and Pliocene basalts were formed during at least six volcanic events that occurred within 50 km of the repository. Three of these events occurred at approximately 3.7, approximately 1, and approximately 0.08 million years ago, and are in or near Crater Flat, within 20 km of Yucca Mountain (Figures 5-29 and 5-34). The Quaternary volcanoes in the Yucca Mountain region occur to the south, west, and northwest of Yucca Mountain in a roughly linear zone defined as the Crater Flat volcanic zone. Models that relate volcanism and structural features in the Yucca Mountain region have emphasized this zone because of the timing of volcanic events and because of its location relative to the repository (BSC 2004c, Sections 6.1.1.1 and 6.4.1.5).

Aeromagnetic data have been gathered at a variety of scales in the Yucca Mountain region. Some aeromagnetic anomalies have been interpreted as buried or partially buried basaltic centers. An anomaly in the northern Amargosa Valley has been sampled by drilling and has been confirmed to be buried basalt with an age of about 3.8 million years (CRWMS M&O 1998c, Chapter 2). Of the aeromagnetic surveys conducted, some provide no evidence of buried basalt and others are equivocal, while several surveys provide evidence of buried volcanic centers (O'Leary et al. 2002). A high-resolution aeromagnetic survey conducted in 1999 recorded a number of small dipole anomalies in Crater Flat and the northern Amargosa Desert. The physical characteristics of the modeled bodies, and the fact that they tend to be aligned along major structural trends, suggest that at least some of the anomalies could represent small-volume basaltic volcanic centers buried at depths between 150 and 350 m (O'Leary et al. 2002). The most recent aeromagnetic survey was completed on June 7, 2004, comprising over 15,000 flight-line miles covering a 333 mi^2 area. These data were used to determine where to drill holes to explore for potential buried basalt to increase confidence in assessments of the probability of igneous activity disrupting the repository. Figure 5-24 shows the outline of the area investigated and the new boreholes. Figure 5-29 shows the results of the previous as well as the more recent investigations. A description of the drilling and the results can be found in SAR Section 2.3.11.2.1.1.

Studies of the eruptive and subsurface effects of basaltic volcanism in the Yucca Mountain region have been conducted using both site-specific and analogue data. The data obtained were used to assess the consequences of a possible future volcanic eruption in the vicinity of the repository (SNL 2007j, Section 6.3). Details on the results of igneous activity evaluations can be found in SAR Section 2.3.11.

5.2.1.5.3.2 Probabilistic Volcanic Hazard Analysis Process

To assess the probability of a future volcanic event intersecting the repository, a hazard study was conducted (CRWMS M&O 1996). The product of the PVHA is a quantitative assessment of the probability of a basaltic dike intersecting the repository and the uncertainty associated with the assessment (BSC 2004c, Section 6.3.1.5). SAR Section 2.2.2.2 provides a comprehensive discussion of the PVHA.

To ensure that a wide range of perspectives was considered in the hazard analysis, individual judgments were elicited from an expert panel composed of 10 members (SAR Section 5.4.1). The experts developed temporal and spatial models of volcanic activity for the hazard calculation. Temporal models describe the frequency of occurrence of volcanic activity and include homogeneous and nonhomogeneous (time-varying) models. Homogeneous Poisson temporal models assume a uniform rate of volcanism based on the number of volcanic events that occurred during various periods in the past. Nonhomogeneous temporal models were used to describe volcanic clustering in time, or to describe the possible waning and waxing of volcanic activity in the region (BSC 2004c, Section 6.3.1.3).

To capture the uncertainty in the location of future volcanic events in the Yucca Mountain region, the PVHA experts used a variety of spatial models to reflect the diversity and range of scientific interpretations. The majority of PVHA experts attributed the areas of greatest frequency of future volcanic activity to the Crater Flat basin because of the frequency of past volcanic activity in that area (BSC 2004c, Section 6.1.1.1 and Figures 6-7a and 6-7b; CRWMS M&O 1996, Section 3).

5.2.1.5.3.3 Probabilistic Volcanic Hazard Analysis Results

The product of the PVHA was a quantitative probability distribution of the annual probability of a basaltic dike intersecting the repository footprint. Separate probability distributions were computed by each of the 10 experts. From these individual probability distributions, which typically spanned approximately 2 orders of magnitude, an aggregate probability distribution was computed that reflected the uncertainty across the entire expert panel. The distributions of the individual experts were combined using equal weights. Updated for the license application repository footprint, the mean annual frequency of intersection of the repository by a volcanic event (i.e., dike) is 1.7×10^{-8}

and 1.3×10^{-8} for an eruption through the repository, conditional on a dike intersection (BSC 2004c, Table 7-1). The majority of the uncertainty in characterizing the hazard arose from uncertainty in an individual expert's evaluations of the hazard, rather than expert to expert differences in interpretations (CRWMS M&O 1996, Section 4.2 and Figures 4-32 and 4-33).

To evaluate the effects of a volcanic event within the repository, information was needed on the length and orientation of the intersecting dike and the probability that the vent above the conduit feeding an erupting volcano forms within the repository footprint and intersects waste. These assessments were developed subsequent to completion of the PVHA on the basis of experts' evaluation of the number of volcanic events that have occurred in the Quaternary, including appropriate uncertainty, and were incorporated into appropriate analyses and models (BSC 2004c, Section 6.5.3.2 and Table 7-1).

5.2.1.6 Geologic FEPs Used to Estimate Postclosure Performance

Geologic FEPs included in the process and abstraction models developed for the TSPA are listed in tables presented in SAR Section 2.2. Detailed discussions of the scenario classes are provided in SAR Section 2.2.1. Geology-related FEPs include the general stratigraphy, rock properties, and characteristics of faults and fractures that are used to establish the geometry and characteristics of flow paths for both unsaturated and saturated zone flow and transport models. Seismic-related FEPs that are evaluated include fault displacement and ground motion damage to EBS features. Additional processes and events that are important include seismic-induced rockfall impacts on EBS features. Detailed discussion of these processes and events are provided in SAR Section 2.3.4.

Igneous FEPs important to the TSPA include intrusion into the repository, interactions of the intruded materials with EBS, intersection of the repository by an eruptive conduit, ash fall, and ash-fall redistribution. SAR Section 2.3.11 provides further discussion of igneous processes and the models developed for the TSPA.

5.2.1.7 Potential Geologic Hazards during the Preclosure Phase

A list of potential external hazards for the preclosure phase at Yucca Mountain has been developed (BSC 2008a, Section 4.5). Hazards associated with the postclosure period and their related engineering measures are addressed by the FEPs screening process. SAR Section 2.2 describes the postclosure FEPs screening process, identifies FEP screening decisions as either included or excluded from TSPA, identifies the basis for FEP exclusion decisions (i.e., excluded based on consequence, probability, or regulation), and provides the TSPA dispositions for included FEPs. Preclosure hazards initiated by external events include geologic natural hazards identified on the basis of known or predicted geologic characteristics. SAR Section 1.6.1.2 describes the initial screening process for generic external hazards. To evaluate external events for relevance during the preclosure period, four questions are asked for each external event category (BSC 2008a, Section 4.5):

1. Can the external event occur at the repository?

2. Can the external event occur at the repository with a frequency greater than 10^{-6}/yr, that is, have a 1 in 10,000 chance of occurring in the 100-year preclosure period?

3. Can the external event severe enough to affect the repository and its operation occur at the repository with a frequency greater than 10^{-6}/yr, that is, have a 1 in 10,000 chance of occurring in the 100-year preclosure period?

4. Can a radioactive release that results from the external event severe enough to affect the repository and its operations, occur with a frequency greater than 10^{-6}/yr, that is, have a 1 in 10,000 chance of occurring in the 100-year preclosure period?

The *Preclosure Seismic Design and Performance Demonstration Methodology for a Geologic Repository at Yucca Mountain Topical Report* (DOE 2007) cites the updated *American National Standard, External-Events PRA Methodology* (ANSI/ANS-58.21-2007) as a source of the standard practice for numerous seismic risk assessment references. Potential external geologic hazards for the 100 year operational period include drift degradation flooding; sandstorm; seismic activity, including earthquake ground motion and surface and subsurface fault displacement; and ash fall from volcanism. These potential geologic hazards are summarized in SAR Section 1.6.3.2. The rockfall hazard under seismic loading conditions is discussed in SAR Section 2.3.4.4.

The potential for rockfall and size of caved blocks due to preclosure seismic ground motions in the intersection of the access main and turnout were evaluated for preclosure ground motion in *Prediction of Rockfalls in Nonemplacement Drifts due to Preclosure Seismic Ground Motions* (BSC 2007d). The analysis determined the probabilities that different sizes of the block could strike the transporter during the movement of waste packages to the emplacement drifts. The distribution of block sizes of the caved rock for a mean annual probability of exceedance is similar for the emplacement drift (slightly smaller) and the intersection of the emplacement drift with the main tunnel, although the mean and median block sizes are larger in the intersection than those predicted for the emplacement drift. The mean and median weights of blocks in the emplacement drift are 0.22 MT and 0.10 MT, respectively, while the weight of the largest unstable block in the emplacement drifts is 2.7 MT (BSC 2004h, Table 6-20). In the intersections the mean and median weights of blocks are 0.28 MT and 0.12 MT, respectively, while the weight of the largest unstable block in the intersections is 36.7 MT. As can be seen, although the mean and median weights of blocks in emplacement drifts and intersections are similar, the largest predicted unstable block (mass of 36.7 MT) predicted in the intersection is much larger than the largest unstable block (2.7 MT) predicted in the emplacement drift.

5.2.1.8 Developments in Geologic Data and Models During Site Characterization

Geologic studies provided a reasonable description of the stratigraphy, volcanic history, and general tectonic setting prior to the beginning of formal site characterization. Observations in the ESF were useful for confirming the nature and location of stratigraphic contacts, as well as the characteristics of major structural features at depth. Information about the spatial variability in rock properties was also gained through testing and observations. The site characterization program included seismic and volcanic investigations intended to fill gaps in and expand the knowledge related to probabilities of volcanic and seismic disruptions. Data collection and analysis, as well as two expert elicitations (the PSHA and PVHA are also summarized in SAR Sections 5.4.2 and 5.4.1), were used to develop the estimates for probabilities and consequences. Section 5.2.1.5.2 provides a summary of the expert elicitation for seismic hazards, and Section 5.2.1.5.3 describes the current understanding of volcanism at Yucca Mountain and summarizes the expert elicitation results. This elicitation produced quantitative probability distributions of the annual probability of a basaltic dike intersecting the repository footprint (BSC 2004a, Section 4.2.4.2).

Insights and confidence about the volcanism study results were gained by conducting the igneous consequences peer review (Detournay et al. 2003). The final report of this comprehensive evaluation of the technical basis used to analyze the consequences of igneous events concluded that "current assumptions about release of radionuclides, both into the atmosphere and into groundwater, are realistic or conservative (in some cases, overly conservative) given the models used for the interactions considered." The panel also found the overall conceptual model for interactions of igneous material with repository drifts to be adequate and reasonable (Detournay et al. 2003, Chapter 5).

5.2.2 Overview of the Hydrology of the Yucca Mountain Site

The underground facility at Yucca Mountain will be located about 200 to 500 m below the surface, at a depth that is approximately 300 m above the water table. The deep water table and thick unsaturated zone result from a combination of low annual precipitation, low infiltration rates, and high rates of evaporation in the arid environment. The water table resides in a volcanic tuff aquifer with flow generally to the south toward Amargosa Valley; below the tuff aquifer is a regional carbonate aquifer. Volcanic tuff and sedimentary confining units separate the volcanic aquifer from the regional carbonate aquifer. Figure 5-39 provides a schematic diagram showing the hydrologic setting of Yucca Mountain.

This section briefly describes the general hydrogeologic features of the Yucca Mountain site, followed by a summary of the regional hydrologic framework and the conceptual models for the unsaturated and saturated zones. Detailed information about the unsaturated zone hydrogeologic features and parameters that are important for developing the conceptual and numerical flow models supporting the TSPA is provided in SAR Section 2.3.2. For the saturated zone, the features and parameters of interest for flow modeling are described in SAR Section 2.3.9. This section also includes a summary of surface water features and characteristics that could potentially affect preclosure repository operation. A discussion of the attributes of the hydrogeologic system that are important in estimating repository performance is followed by a brief summary of the evolution of hydrogeologic understanding since the beginning of site characterization.

5.2.2.1 Hydrogeologic Features of the Yucca Mountain Site

Unsaturated Zone—The hydrogeologic features and characteristics at Yucca Mountain are the result of the volcanic origin of the ash-flow and ash-fall tuffs that make up the thick unsaturated zone. The cooling history of the tuffs influenced their mechanical and hydrologic properties, resulting in heterogeneous layers of fractured volcanic rock characterized by various degrees of welding, faulting, and hydrothermal alteration. This heterogeneity results in variability in hydraulic parameters and has important effects on flow paths. The major geologic units are subdivided into the following unsaturated zone hydrogeologic units on the basis of properties that are important to flow and transport modeling:

- Tiva Canyon welded (TCw)
- Paintbrush nonwelded (PTn)

- Topopah Spring welded (TSw)
- Calico Hills nonwelded (CHn)
- Crater Flat undifferentiated (CFu).

Figure 5-40 shows these hydrogeologic units and the key features and processes of the Yucca Mountain unsaturated zone (BSC 2004a, Section 7). SAR Sections 2.3.1, 2.3.2, and 2.3.8 describe the data and models used to represent flow and transport in the unsaturated zone. See Figure 5-30 for a comparison of various nomenclatures used to describe rock units at Yucca Mountain.

Welded units typically have low matrix porosities (about 10%) and high fracture densities, whereas nonwelded and bedded tuffs have relatively high matrix porosities (about 30%) and low fracture densities. The TSw unit is the repository host rock. The rock unit below the repository host rock is the Calico Hills Formation, which is unaltered (vitric) in the southern part of the site area, contains rare fracturing, and has high matrix permeability. In the northern part of the site area, the Calico Hills Formation is strongly altered to zeolite and clay, with resulting low permeabilities and sparse fractures (BSC 2004a, Sections 3.3.6.4 and 7.9.1.4).

Flow through the unsaturated zone is partitioned between fractures and matrix and redistributed by lateral flow down-dip along horizons generally defined by bedding planes. In some cases, the PTn unit (the hydrostratigraphic unit above the repository level) may laterally divert downward-percolating water. Below the repository, lateral diversion of unsaturated zone waters is associated with low permeability zeolites immediately above and within the CHn unit, and has led to development of perched water zones (BSC 2004a), Section 7.9.1.4).

Matrix properties developed from core data for the various unsaturated zone hydrogeologic units are provided in SAR Table 2.3.2-3. These properties include the following:

- Porosity
- Permeability
- Parameters for estimating partitioning of water between fractures and matrix
- Residual liquid saturation.

SAR Table 2.3.2-4 provides permeabilities for the major unsaturated zone units important for modeling flow and transport. SAR Section 2.3.2.2 provides a further discussion of matrix, fracture, and fault properties that are important to modeling unsaturated zone flow.

The flow behavior within the unsaturated zone can be summarized as follows (SAR Section 2.3.2.2.1):

- Subsurface flow occurs in a heterogeneous system (welded versus nonwelded) of layered, anisotropic, fractured volcanic rocks.

- Spatially and temporally variable infiltration pulses move rapidly through the fractures in the TCw unit, with little attenuation by the matrix.

- Attenuation effects within the PTn unit result in nearly steady-state liquid-water flow below this unit.

- Fracture flow is dominant in welded units (TCw and TSw), while matrix flow is dominant in nonwelded units (PTn).

- Below the PTn, isolated, transient, and fast-flow paths may exist but are expected to transmit only a small amount of liquid water.

- Below the repository, low-permeability layers and perched water bodies in the CHn may channel some flow laterally to faults that can act as conduits for water flow to the water table. There are also perched water bodies north of the repository, along the base of the TSw, which are at a higher elevation than the repository footprint (SNL 2007c, Sections 6.6.2.2).

Saturated Zone—The hydrogeologic features of the saturated zone at Yucca Mountain result from a combination of rock type, structural setting, geochemical history, and burial depth. As noted above, the water table occurs about 300 m below the repository. The Topopah Spring Tuff dips beneath the water table at several places east and south of the repository, and comprises the upper volcanic aquifer. The rest of the saturated zone under the repository is in the Calico Hills Formation, an aquitard, and the Crater Flat Group, which is called the lower volcanic aquifer. A deeper aquifer also exists beneath the site, which is called the regional carbonate aquifer.

The saturated zone site-scale conceptual model is a synthesis of what is known about flow processes at the scale required for both process level modeling and TSPA calculations. This knowledge builds upon, and is consistent with, information collected across the regional scale, but it is more detailed because a higher density of data is available at the site-scale. Information from geologic maps and cross sections, borehole data, fault-trace maps, and geophysical data were used to develop a three-dimensional interpretation of the hydrostratigraphy and geologic structure of the saturated zone site-scale flow model.

Rock stratigraphies are grouped into 27 hydrogeologic units that are classified as having either relatively large permeability (aquifers) or relatively small permeability (confining units). The position and geometry of these hydrogeologic units and the major faults control groundwater flow. The source of most of the groundwater flow in the saturated zone domain is lateral flow through the western, northern, and eastern boundaries. A small portion (approximately 10%) of the total flux through the saturated zone site-scale domain is thought to be from precipitation and surface runoff infiltrating along Fortymile Wash.

Outflow from the site-scale region is chiefly to Amargosa Valley. A small amount of water is removed by pumping wells located in the Amargosa Valley near the southern boundary of the model domain. As groundwater moves away from the repository, it first flows through a series of welded and nonwelded volcanic tuffs with relatively low specific discharge. These flow paths eventually pass into alluvium (SNL 2007b, Section 8.1.2).

The saturated zone is a potential pathway for transport of radionuclides to the accessible environment. Flow is predominantly lateral, and the horizontal hydraulic gradient beneath Yucca Mountain is small. Hydraulic heads upgradient and downgradient from the repository have been used to define a generally southeasterly and southerly flow direction from Yucca Mountain. Flow through the fractured tuff aquifers is generally confined to isolated fracture intervals, whereas an alluvial aquifer, which is encountered at 10 to 20 km along the downgradient flow path, has dispersed flow through the porous material. Saturated alluvium is the principal hydrogeologic unit at the accessible environment. SAR Section 2.3.9 provides further discussion of saturated zone features and processes at Yucca Mountain.

Saturated zone hydraulic properties include hydraulic conductivity on a smaller scale and transmissivity on a larger scale. Respectively, the two scales are characterized by tests on core samples and in boreholes. Multiple borehole tests have provided storage and dispersion coefficients for the saturated flow system. Each of these tests was designed to determine specific attributes of the rock or sediment unit tested. Matrix properties in the saturated volcanic tuffs are important for basic characterization information, although, as noted, flow is generally through fractures and faults. For this reason, measurements of rock matrix properties play a relatively small role in understanding the large-scale flow system. However, estimates of fluid storage must account for the volume in the rock matrix, and diffusion into the pore space within the rock matrix may be an important process in retardation of radionuclide transport. SAR Section 2.3.9.3.2 provides additional details on the role of matrix diffusion in saturated zone transport models.

The specific discharge downgradient from the repository, along with effective transport porosity, determines the rate at which groundwater moves beneath and away from Yucca Mountain. The specific discharge, in turn, is a function of the permeability of the rocks and alluvium, and the hydraulic gradient (BSC 2004a, Section 8.3.3.4).

More than 150 individual hydraulic tests have been conducted since 1997 in boreholes on and around Yucca Mountain to determine rock mass properties. The various hydraulic parameters discussed above have been combined to calculate the permeabilities in the saturated zone rock and alluvium units. Permeability data exhibit a range of values depending on scale, lithology, and proximity to faults and fractures. It is well recognized that scale effects on permeability measurements are significant in that core measurements will not capture the permeability that results from fractures and fracture networks. Thus, modeling approaches generally rely on measurements made at the largest scales. SAR Section 2.3.9.3.3.2 describes the approach used to incorporate uncertainties into saturated zone models to account for the effects of scaling parameter values from the scale of measurement to the scale of interest.

Field testing relating to the saturated zone modeling studies provides the basis for model development in SAR Sections 2.3.9.2 and 2.3.9.3.

The most significant conclusions from in situ field testing (SNL 2007a, Section 7.1) with regard to the saturated zone are the following:

- The saturated volcanic tuffs near Yucca Mountain can be treated as an equivalent porous medium. The fracture networks in the tuffaceous rocks are connected well enough that hydraulic responses are similar to those observed in porous media. However, the flow system exhibits layered heterogeneity with layers of high permeability often associated with relatively narrow fractured intervals. Also, larger-scale hydraulic characteristics of the saturated tuffs are strongly influenced by structural features (such as faults).

- Horizontal anisotropy in hydraulic conductivity in the saturated fractured volcanic tuffs near Yucca Mountain, as determined from drawdown responses in distant wells during the 1996 to 1997 long-term pumping test in UE-25 C#3, is oriented roughly north-south (direction of greatest conductivity) with an anisotropy ratio of about 4:1 (Figure 5-11).

- Solute tracer responses in cross-hole tracer tests at the C-Wells were consistent with a dual-porosity conceptual transport model (Figure 5-11). Solute migration occurs primarily in flowing fractures. The solutes are effectively attenuated by diffusion into stagnant water in the porous rock matrix (matrix diffusion).

- Apparent sorption of an ion-exchanging tracer (lithium) was generally greater in field tracer tests in the volcanic tuffs than in laboratory tests using the same materials. These results suggest that laboratory sorption parameters will tend to result in overestimation of radionuclide transport rates in the tuffs.

- Polystyrene microsphere responses in cross-hole tracer tests at the C-Wells suggest that filtration processes effectively attenuate a large percentage of the microspheres over relatively short distances. However, some of the filtered microspheres later detach from fracture surfaces and continue to migrate. Also, flow transients appear to be capable of initiating detachment.

- Hydraulic testing in the saturated alluvium at the Nye County Alluvial Testing Complex and Site 22 locations south of Yucca Mountain has indicated that the alluvium behaves as an unconfined aquifer at shallow depths, and then transitions to a leaky-confined or confined aquifer system beneath the first significant confining layer. The results indicate that subhorizontal confining or semi-confining layers exist in the alluvium, but insufficient data exist to predict their depth and lateral extent as a function of location. Composite horizontal hydraulic conductivity estimates from cross-hole hydraulic testing in the alluvium are on the order of 2 m to 5 m/day, with individual isolated zones having horizontal conductivities as high as 12 m to 13 m/day.

5.2.2.2 Summary of Regional Groundwater Flow System

This section provides an overview of the regional groundwater flow system, including the features that affect local and regional groundwater supply.

5.2.2.2.1 Regional Framework

Yucca Mountain is located in the Great Basin, which is an internally drained region of the Basin and Range Province (Figure 5-28). Both surface water and groundwater drainage systems terminate in hydrologic sinks, from which water returns to the atmosphere by evaporation or plant transpiration (BSC 2004a, Section 8.2.1).

The Yucca Mountain site is located within the central Death Valley subregion of the Death Valley regional groundwater flow system (Figure 5-41). Movement of groundwater into, through, and out of the regional flow system depends on the topography and geology of the region. The topography of the region is expressed by linear, generally northwest-southeast-trending, fault-bounded mountain ranges that are separated by broad (20 to 30 km) alluvial valleys and basins. Topographic relief between valley floors and adjacent mountains locally exceeds 1,500 m, and valley and basin floors are local depositional centers often containing playas that act as catchments for surface water runoff. Playas are seldom occupied by surface water, although numerous playas contain saline deposits resulting from evaporation of surface water or shallow groundwater from the playa surface in the past (BSC 2004a, Section 8.2.1).

The hydrology of the region is dominated by the prevailing present-day arid climatic conditions (BSC 2004a, Section 6.4.1.2.3) that restrict the quantities of water available to sustain surface water drainage systems and recharge underlying groundwater flow systems. Figure 5-42 illustrates the major surface water features in the region. The Amargosa River and its tributaries constitute the major fluvial system within the region, which, under present-day climatic conditions, is a system in which flow occurs only in response to infrequent heavy precipitation events or for short distances as a result of spring discharge in the channel system. The salt pan that occupies the floor of Death Valley is the ultimate discharge area, or sink, for the overall regional hydrologic system (BSC 2004a, Section 8.2.1). The Death Valley regional groundwater flow system has an area of approximately 70,000 km^2, all in Nevada and California (BSC 2004a, Sections 8.2.1 and 8.2.2).

The eastern and southern parts of the Death Valley region lie within the carbonate-rock province of the Great Basin, which is characterized by thick sequences of carbonate rock. These rocks form a generally deep regional aquifer and allow interbasin transfer of groundwater in the Death Valley region. The deep aquifer in the Yucca Flat and Frenchman Flat areas of the Nevada Test Site results from drainage of groundwater from the valley fill into the underlying and surrounding carbonate-rock aquifer. In other valleys, such as the Amargosa Desert, southern Indian Springs Valley, and possibly eastern Jackass Flats, interbasin movement of groundwater is upward. Consequently, hydraulic connections can be inferred to exist between the valley-fill aquifers and deeper carbonate-rock aquifer throughout much of the region (BSC 2004a, Section 8.2.2).

5.2.2.2.2 Regional Hydrogeology

The Death Valley regional groundwater flow system is defined by the regional groundwater flow model domain developed by D’Agnese, Faunt et al. (1997); D’Agnese, O’Brien et al. (2002); and Belcher (2004). The model is a three-dimensional numerical groundwater flow model that synthesizes the current understanding of the hydrogeology and hydrology of the regional groundwater flow system. The regional boundaries define the flow model boundaries. In this way, the major hydrogeologic features are incorporated and determine and control the movement of groundwater into and out of the system (D’Agnese, O’Brien et al. 2002, p. 36).

Conceptual Model—The regional groundwater flow system constitutes a partially closed groundwater basin that is composed of surficial Quaternary alluvial and valley-fill deposits, Tertiary volcanic rocks (principally tuffs), Mesozoic volcaniclastic and sedimentary rocks, and Paleozoic carbonate and clastic rocks that, in turn, overlie Precambrian granitic and metamorphic basement rocks (BSC 2004a, Section 8.2.9).

The stratigraphic units of the regional groundwater flow system define the principal aquifers and confining units that control the movement of groundwater. In particular, highly transmissive carbonate rocks of Early Paleozoic age are pervasive in the subsurface and in outcrops throughout the region. This lower carbonate aquifer exerts major control on the overall regional groundwater flow system. The region is partitioned structurally into a complex of tilted fault blocks that juxtapose hydrogeologic units of differing hydrologic properties, leading to heterogeneity in the flow system. The nature of the fault zones produces major effects on groundwater flow. Faulting can produce zones of intense fracturing, and can create highly permeable channels that are enhanced by dissolution in the carbonate aquifer. Alternatively, faulting and folding in some rock types can create barriers, and the groundwater rises to the surface as springs or diffuse discharge. Consequently, groundwater flow paths within the regional flow system are complex (BSC 2004a, Section 8.2.9).

The conceptual model considers that water enters the system as interbasinal underflow and as recharge from precipitation in upland areas. The geographic distribution of rainfall and snowfall is principally a function of land surface elevation, which means the highland areas receive most of the precipitation and consequently provide most of the recharge to the groundwater system (BSC 2004a, Section 8.2.2.3). Because of present-day arid conditions, virtually no recharge or perennial surface water flow occurs in the lowlands and valley floors. Groundwater flow paths within the system diverge from the highlands and are superimposed on deeper regional flow paths that are largely controlled by flow in the lower carbonate aquifer. The overall direction of flow is toward Death Valley (Figure 5-41), although there are a number of localized discharge areas, such as Cactus Springs and Indian Springs (BSC 2004a, Section 8.2.9).

Yucca Mountain is located in a subsection of the Death Valley regional groundwater flow system called the Alkali Flat–Furnace Creek groundwater basin (Figure 5-41) (BSC 2004a, Section 8.2.8.1.1). Water is recharged locally in the northern volcanic highlands and moves laterally southward toward Yucca Mountain through the underlying fractured volcanic rock aquifers into the valley-fill deposits that occupy the floors of the intermontane basins adjacent to Yucca Mountain. Ultimately, discharge occurs as spring flow or evapotranspiration in the southern part of the basin. In the northwestern part of the basin, subregional groundwater flow is dominantly lateral and downward into the underlying regional lower carbonate aquifer. Near Yucca Mountain, however, data from UE-25 p#1 (the only borehole that penetrates the carbonate aquifer) indicate hydraulic gradients are upward from the lower carbonate aquifer into the overlying volcanic units, which implies that, if connected, water could tend to move upward from the carbonate rocks into the overlying volcanic rocks. A three-dimensional coupled flow and heat transport model was used to show that the thermal high coinciding with the Paintbrush fault zone can be explained without significant upwelling from the underlying aquifer. Instead, the thermal anomaly is consistent with thermal conduction enhanced slightly by vertical groundwater movement within the volcanic aquifer sequence (Painter et al. 2003). These results are not inconsistent with the site and with regional hydraulic gradient data that indicate a high potential for such upward flow. In the south-central part of the basin, near the Nevada–California border, groundwater flow is dominantly upward from the lower carbonate aquifer into the subregional system and toward discharge areas along the Amargosa River, Carson Slough, and Alkali Flat. This information implies that the regional lower carbonate aquifer is hydraulically connected with and exerts control on the water table elevations in the overlying alluvial and volcanic rock aquifers throughout the groundwater basin (BSC 2004a, Section 8.2.8.1.1).

A groundwater divide in the southern Grapevine Mountains separates Death Valley (the Funeral Mountains section) from the Amargosa River section of the groundwater basin. A major intermediate discharge area occurs at Alkali Flat, which is a playa at the southern edge of the Alkali Flat–Furnace Creek groundwater basin (Figure 5-41). Groundwater and intermittent surface flow breach the southern boundary along the Amargosa River, providing inflow to the southern Death Valley subregion. Beyond the springs at Furnace Creek, groundwater flows toward the salt pan on the floor of Death Valley and is discharged either by stands of mesquite on the lower part of the Furnace Creek fan or by evapotranspiration from the Death Valley salt pan (BSC 2004a, Section 8.2.8.1.1).

5.2.2.3 Site Hydrology and Conceptual Models

This section describes the site hydrogeologic system, including both the unsaturated and saturated zones. The purpose of this section is to provide an overview of the results of site characterization in terms of the understanding that has been gained about those aspects of hydrology that are important to repository performance.

5.2.2.3.1 Unsaturated Zone Hydrostratigraphy and Hydrology

In the unsaturated zone, infiltration and subsequent percolation to the water table involve dominantly vertical flow, so the area of principal interest is the immediate vicinity of Yucca Mountain. The principal hydrogeologic units defined in the unsaturated zone at the site are surficial deposits of unconsolidated alluvium, TCw, PTn, TSw, CHn, and CFu (Table 5-3 and Figure 5-43). These hydrogeologic units, together with natural hydrologic processes, control water and gas movement in the unsaturated zone. Processes of interest include net infiltration, percolation, fracture–matrix interaction, accumulation of perched water, lateral flow, and deep percolation to the water table. These processes determine the amount of water that can seep into repository drifts and possibly come in contact with waste packages, thus enabling the dissolution and transport of radionuclides away from the repository. The occurrence of these processes, especially percolation, is affected by the specific sequencing of hydrogeologic units, as well as transitions between them (BSC 2004a, Section 7).

Following are brief descriptions of the primary unsaturated zone hydrogeologic units, starting from the surface and moving downward to the water table.

Surficial Deposits—These deposits are generally fluvial sediments and fluvial debris-flow deposits that are found in the basins, washes, and alluvial fans. In the soil depth analysis for infiltration modeling (BSC 2006b), soil refers to unconsolidated surficial deposits that range in composition from talus accumulations of cobbles and boulders to fine-grained eolian deposits. Soil depth data are used directly in the infiltration model for the Yucca Mountain repository (SNL 2008a, Table 4-1).

The fluvial sediments and fluvial debris-flow deposits that are found in the basins, washes, and alluvial fans range from greater than 100 m thick in the valleys to less than 30 m thick in the mouths of the washes. More stable surfaces, generally on the ridgetops, have developed soils ranging in thickness from bare rock to greater than 2 m thick with high clay contents (BSC 2004a, Section 7.1.3.4).

TCw Unit—This unit is the most prevalent hydrogeologic unit exposed at the land surface. It is composed of moderately to densely welded, highly fractured pyroclastic flow deposits with a maximum thickness of about 150 m along Yucca Crest (BSC 2004a, Section 3.3.6.1). At the transition to the underlying nonwelded tuff unit (the PTn), the tuffs grade gradually downward over a few tens of centimeters from densely welded to nonwelded, accompanied by an increase in matrix porosity and a decrease in fracture frequency. Many fractures in the lower TCw unit terminate at the contact between the TCw and the PTn units. Alteration to clay minerals is common at the base of the TCw unit and is correlated with observed increases in saturation (BSC 2004a, Section 3.3.6.1).

PTn Unit—This unit consists of layers of predominantly nonwelded and bedded tuffs (particularly in the repository area) with high matrix porosity and low fracture frequency (SNL 2007c). The combined thickness of the PTn layers range from 150 m in the north of the model area to 30 m or less, even completely disappearing in several areas of the south. However, the PTn unit is present over the entire repository area, where the thickness of the PTn unit ranges from approximately 30 to 60 m, and it is even thicker to the north of the repository (SNL 2007c, Section 6.2.2). The model area encompasses a larger area than the footprint of the repository. SAR Figure 2.3.2-4 shows the PTn thickness in the vicinity of the repository footprint. This figure shows that the PTn has a minimum thickness of 20 m (66 ft) over the repository footprint, and becomes thinner only in limited regions outside of the waste emplacement area. Lateral variation in welding and variable distribution of altered intervals cause properties within the PTn to be highly heterogeneous. Through-going fracture networks are rare and are typically associated with faults. The high porosity of the rock matrix effectively dampens infiltration and distributes the downward flow of water. The bottom of the PTn unit is defined as the contact between the moderately and densely welded, crystal-rich vitric subzones. At the transition from the PTn unit to the underlying TSw unit, a thin alteration zone may behave as a capillary or permeability barrier to flow and could create locally saturated conditions (BSC 2004a, Section 3.3.6.2).

TSw Unit—This unit contains the repository horizon and is composed of moderately to densely welded deposits with intense fracturing. At the base is a densely welded glassy vitrophyre, which reflects a zone of rapid cooling. The thickness of the TSw unit ranges from about 280 to 350 m in the repository area. At the TSw unit transition to the underlying CHn unit, the tuffs grade from densely welded to nonwelded over several meters, accompanied by an increase in matrix porosity and a decrease in fracture frequency. Much of the vitric material occurring above and below this boundary has been altered to clays or zeolites (BSC 2004a, Section 3.3.6.3).

CHn Unit—This unit consists of mostly nonwelded tuffs (about 180 to 320 m thick in the repository area) with highly variable zeolite distribution. Zeolite abundance increases to the north and east across the repository area, as well as with depth. Major vitric (unaltered) areas in the CHn lie in the southern half of the repository area (BSC 2004a, Section 3.3.6.4).

CFu Unit—This unit is a relatively small volume of rock with the unsaturated thickness ranging from 0 m up to about 140 m just above the water table beneath the western-southwestern portions of the repository (BSC 2004a, Section 3.3.6.5).

5.2.2.3.1.1 Unsaturated Zone Conceptual Model

The conceptual model of unsaturated zone flow processes provides the basis for developing numerical models to predict flow paths under present-day and future climate conditions. The development of such a conceptual model is based on the geologic setting of the unsaturated zone and the variety of data collected from the unsaturated zone, in addition to theoretical and numerical studies conducted in the last two decades. Figure 5-43 schematically shows the overall conceptualized water flow behavior in the unsaturated zone, including the relative importance of fracture and matrix flow in the various hydrogeologic units.

Net infiltration (water infiltrating below the zone of evapotranspiration) is the ultimate source of percolation flux at the repository horizon. Net infiltration is spatially and temporally variable because of the nature of the storm events that supply precipitation and variations in topography, soil thickness and hydraulic properties, bedrock permeabilities, and effects of evapotranspiration.

Infiltration is higher on side slopes and ridgetops, where bedrock is exposed, and fracture flow in the bedrock is able to move moisture away from zones of active evapotranspiration. Soil depth is one of the most significant factors controlling local net infiltration. Areas with very shallow soils (0.1 to .05 m) and areas with no soil dominate the total predicted net infiltration over the full domain (SNL 2008a, Section 6.5.7.6.1).

Near-surface infiltration data suggest that significant net infiltration occurs only every few years. In those few years, the amount of net infiltration varies greatly, depending on storm amplitudes, durations, and frequencies. In very wet years, water may infiltrate into Yucca Mountain during a relatively short time period (BSC 2004a, Section 7.9.1.1).

Between these episodic infiltration events, there is little to no net infiltration (CRWMS M&O 1997b, p. 3-7; SNL 2008a, Section 7.2.3). Net infiltration pulses are expected to move rapidly through the fracture system in the TCw hydrogeologic unit as a result of the relatively high density of interconnected fractures and low matrix permeabilities (BSC 2004a, Section 7.9.1.2). This expectation is supported by pneumatic data that show little attenuation of the atmospheric barometric signal in the TCw unit (BSC 2004a, Section 7.9.1.2).

The predominant fracture flow in the TCw unit becomes predominantly matrix flow in the PTn unit because of the relatively high matrix permeability and porosity and the low fracture density of the PTn unit (Figure 5-43). As a result, the PTn unit greatly attenuates infiltration pulses, so that liquid water flow below the PTn unit is approximately in steady state (BSC 2004a, Section 7.9.1.2). At the initiation of site characterization, it was hypothesized that significant lateral flow occurs within the PTn unit in response to the capillary-barrier effect and the extremely low net infiltration (Montazer and Wilson 1984, pp. 45 to 47). However, observed field liquid saturation and geochemical isotopic data collected during site characterization are consistent with spatially limited lateral flow in the PTn hydrogeologic unit (BSC 2004a, Section 7.9.1.2).

Unsaturated flow of liquid water in the TSw hydrogeologic unit is primarily through fractures. The calculated matrix percolation rate is a small fraction of the average infiltration rate that is currently estimated. Therefore, the remainder of the flow in the TSw unit must be distributed in the fracture network. Calcite coating data show that, in the welded units, most of the deposition is within fractures or on the floor of lithophysal cavities intersected by fractures, which supports the hypothesis that fracture flow is a major flow mechanism within the TSw unit (BSC 2004a, Section 7.9.1.2). The occurrence of perched water in a number of boreholes in the lower part of the TSw hydrogeologic unit and the upper part of the CHn hydrogeologic unit (UZ-14, SD-7, SD-9, SD-12, NRG-7a, G-2, and WT-24 (SNL 2007c, Section 6.2.2.2) indicates that vertical flow has been impeded by a decrease in permeability and fracture density, resulting in down-dip lateral flow (BSC 2004a, Sections 7.4.2 and 7.9.1.4).

The main hydrogeologic units below the repository are the CHn and the CFu (Figure 5-43). Both of these units have vitric and zeolitic components that differ by the degree of hydrothermal alteration. The zeolitic rocks of the CHn and CFu units have low matrix permeability, and some fracture permeability, which suggests that a relatively small amount of water may flow through the zeolitic units. Most of the water that percolates to the zeolitic horizon is diverted laterally to perched water bodies and then vertically down faults. Conversely, but similar to the PTn hydrogeologic unit, the vitric rocks of the CHn and the CFu hydrogeologic units have relatively high matrix porosity and permeability. Thus, mostly porous-medium flow predominates in these rocks, and fracture flow is limited (BSC 2004a, Section 7.9.1.4).

Faults cut through the hydrogeologic sequence, including the PTn unit, and allow transient fast vertical flow, reducing the damping effect of the PTn unit on transient infiltration. Net infiltration into the surface expression of a fault depends upon its hydraulic conductivity and how much of the fault area is exposed in surface water drainage basins. Transient flow along faults is not expected to be a major liquid flow mechanism above the repository, because of the relatively small cross-sectional areas of the fault zones exposed at the surface and insignificant transient lateral flow to the faults (BSC 2004a, Section 7.9.1.5).

Seepage into Drifts—Percolating water reaching the repository level will tend to be diverted around the emplacement drift openings because capillary forces hold the water in the rock, as described in SAR Section 2.3.3. Rather than seep into the emplacement drifts, water may also flow along the drift surface without dripping into the opening, or it may evaporate from the drift wall. The end result is that the rate of water dripping into an emplacement drift will be significantly less than the local percolation rate (SAR Section 2.3.3.2).

Multiple in situ tests were performed in the ECRB Cross-Drift to study seepage behavior and to characterize seepage-related properties in different units under different conditions. Test results show that seepage is sensitive to a parameter that reflects capillary strength, permeability, and local percolation flux. These tests provided data to ensure that appropriate spatial variability and uncertainty are included in seepage models. SAR Section 2.3.2.3.2 provides a summary of the results of in situ tests, as well as laboratory experiments that support the development of seepage models.

5.2.2.3.2 Saturated Zone Hydrostratigraphy and Hydrology

Water flow through the fractured tuff aquifers is generally confined to isolated fracture intervals, whereas flow in the alluvial aquifer, downgradient from Yucca Mountain, is dispersed through the porous material. Following are brief descriptions of the primary saturated zone hydrogeologic units in the Yucca Mountain area.

Quaternary–Tertiary Valley-Fill Aquifer—This unit underlies most of the area to the east of Yucca Mountain and south in the Amargosa Desert. It is composed of diverse alluvial sediments, and has a thickness of up to several hundred meters. This aquifer is the main water source for domestic and irrigation use in the Amargosa Valley. The valley-fill aquifer may receive lateral flow and recharge from the volcanic tuffs (BSC 2004a, Sections 8.2.2.1.1, 8.2.8.1.1, and 8.4.2).

Upper Volcanic Aquifer—This unit is equivalent to the Topopah Spring Tuff and is the uppermost volcanic water-bearing unit of the saturated zone. It consists of variably welded and nonwelded tuffs. The Topopah Spring unit is not saturated below the repository, but it becomes saturated to the east and south of Yucca Mountain and in Crater Flat (Luckey et al. 1996, pp. 17 to 21).

Upper Volcanic Confining Unit—This unit consists of lavas, volcanic breccias, and nonwelded to welded tuffs; it commonly contains clay or zeolites. The unit includes the lowermost part of the Topopah Spring Tuff, the Calico Hills Formation, and the uppermost part of the Crater Flat Group (Luckey et al. 1996, pp. 17 to 21).

Lower Volcanic Aquifer—This unit consists of variably welded ash-flow tuffs and lava. It includes most of the Prow Pass Tuff and units from the Crater Flat Group. This aquifer underlies Yucca Mountain but tends to produce less water than the upper volcanic aquifer (Luckey et al. 1996, pp. 17 to 21).

Lower Volcanic Confining Unit—This unit consists of nonwelded and commonly zeolitized units of older tuff units (Luckey et al. 1996, pp. 17 to 21).

Carbonate Aquifer—This unit consists of Paleozoic dolomite and limestone. In the vicinity of Yucca Mountain, the lower carbonate aquifer occurs beneath several thousand meters of Tertiary volcanic units. However, the lower carbonate aquifer was penetrated in borehole UE-25 p#1 at a depth of 1564 meters (Luckey et al. 1996, pp. 17 to 21) southeast of Yucca Mountain (Figure 5-10).

5.2.2.3.2.1 Saturated Zone Conceptual Model

Yucca Mountain is located within the Alkali Flat–Furnace Creek subbasin of the Death Valley regional flow system. Recharge within the Death Valley flow system generally occurs at higher elevations, which receive rainfall and snow. Water inputs to the Alkali Flat–Furnace Creek subbasin include groundwater inflow along the northern boundary of the subbasin, recharge from precipitation in high elevation areas of the subbasin, and recharge from surface runoff in Fortymile Canyon and Fortymile Wash (SAR Section 2.3.9.2).

The groundwater flow direction from Yucca Mountain has been determined based on observations of water level, and measurements of hydraulic conductivity at or near Yucca Mountain. Although the observed hydraulic gradient directly beneath Yucca Mountain is small, water levels upgradient and downgradient from the repository indicate a generally southeasterly groundwater flow direction beneath Yucca Mountain and a generally southerly flow direction in the vicinity of Fortymile Wash. These flow directions near Yucca Mountain are consistent with the general flow directions of the Death Valley regional groundwater flow system (SAR Section 2.3.9.2).

Water flow through the fractured tuff aquifers is generally confined to isolated fracture intervals, whereas flow in the alluvial (valley-fill) aquifer is dispersed through the porous media (SAR Section 2.3.9.2.1). The average flow rate in the alluvium, as defined by the specific discharge (volumetric flow rate per unit cross-sectional area) distribution in the alluvium, has been estimated to be within a range of about 1.2 to 9.4 m/yr (SAR Section 2.3.9.2.2). Groundwater velocities are derived from the estimates of specific discharge and effective porosity that are developed from field testing and supported by radioisotope data.

Much information is available about the regional-scale hydrogeology at Yucca Mountain, both from site characterization activities as well as from numerous hydrogeologic studies that have been conducted at the Nevada Test Site. Available data are sufficient to describe the stratigraphy, structure, and hydraulic properties of component media, recharge and discharge regions, and groundwater flow paths.

The climate in the Yucca Mountain area is arid, and the water table varies from hundreds of meters below ground surface in the northern part of the modeled area to tens of meters below ground surface in the southern part of the modeled area. Natural recharge to the saturated zone is from precipitation percolating through the unsaturated zone. Recharge occurs primarily in mountainous areas where there is more snow and rainfall (i.e., Yucca Mountain, including regions of higher elevation to the north and northeast, and the Spring Mountains 50 km southeast of Yucca Mountain). Estimates of recharge rates at the regional scale are based on empirical relationships of recharge and discharge. Flow paths in the saturated zone are well characterized at the regional scale because numerous water-level measurements are available.

Water-level measurements indicate considerable differences in the magnitude of the hydraulic gradient between areas to the north (large hydraulic gradient), to the west (moderate hydraulic gradient), and to the southeast (small hydraulic gradient) of Yucca Mountain. The hydraulic gradient drives flow from the repository to the south and southeast. A vertical, upward hydraulic gradient from the underlying carbonate aquifer and the deeper volcanic units is also observed in some wells immediately downgradient of Yucca Mountain.

Data on groundwater chemistry indicate significant spatial variability in geochemical and isotopic composition that results from differences in flow paths, recharge locations, and groundwater age. Because the performance of the Yucca Mountain repository is evaluated over thousands of years, the possible impacts of a future wetter climate must be considered. The general locations of areas of recharge and discharge depend primarily on the topography of the land surface. Modeling studies suggest that increased recharge would result in a higher water table and steeper hydraulic gradients. Field mapping of zeolite in both exposures and core and paleospring deposits has confirmed that a higher water table existed during past, wetter climates, and this mapping supports numerical simulations of the possible impacts of climate change.

Geologic studies have identified the important rock types and their spatial distribution. The rock types that play the largest role in regional hydrogeology are Paleozoic carbonates, Quaternary-Tertiary volcanic rocks, and Quaternary-Tertiary sediments and volcanic tuffs that fill structural depressions. Relatively shallow flow occurs in the volcanic rocks and valley fill (primarily alluvium), and deeper flow occurs in the regionally extensive carbonate aquifer. Along the inferred shallow flow path, groundwater flow paths originate in volcanic rocks near the repository site and continue into younger valley-fill deposits at greater distances. The permeabilities of the volcanic rocks near Yucca Mountain are increased by the presence of fractures.

An extensive suite of field observations, interpretations of borehole logs, borehole hydrologic tests, lab-scale tests, and field tracer tests (C-Wells complex) confirms that fractures dominate groundwater flow in the volcanic rocks. However, flow in the alluvium occurs through the primary porosity of these sediments (SNL 2007b, Section 8.1.1).

The most significant conclusions from in situ field testing (SNL 2007a, Section 7.1) with regard to barrier capability of the saturated zone (SAR Section 2.1.2.3) are the following:

- For flow modeling purposes, the saturated volcanic tuffs near Yucca Mountain can be treated as an equivalent porous medium. The fracture networks in the tuffaceous rocks are sufficiently connected that hydraulic responses are similar to those observed in porous media. However, the flow system exhibits layered heterogeneity with layers of high permeability often associated with relatively narrow fractured intervals. Also, larger-scale hydraulic characteristics of the saturated tuffs are strongly influenced by structural features, such as faults.

- Horizontal anisotropy in hydraulic conductivity in the saturated fractured volcanic tuffs near Yucca Mountain, as determined from drawdown responses in distant wells during the 1996 to 1997 long term pumping test in UE-25 c#3, is oriented roughly north–south (direction of greatest conductivity) with an anisotropy ratio of about 4:1 (Figure 5-11).

- Solute tracer responses in cross-hole tracer tests at the C-Wells were consistent with a dual-porosity conceptual transport model. In this model, solute migration occurs primarily in flowing fractures. The solutes are effectively attenuated by diffusion into stagnant water in the porous rock matrix (matrix diffusion) (Figure 5-11).

- Apparent sorption of an ion-exchanging tracer (lithium) was generally greater in field tracer tests in the volcanic tuffs than in laboratory tests using the same materials. These results suggest that laboratory sorption parameters will tend to result in overestimation of radionuclide transport rates in the tuffs.

- Polystyrene microsphere responses in cross-hole tracer tests at the C-Wells suggest that filtration processes effectively attenuate a large percentage of the microspheres over relatively short distances. However, some of the filtered microspheres later detach from fracture surfaces and continue to migrate. Also, flow transients appear to be capable of initiating detachment.

- Hydraulic testing in the saturated alluvium at the Nye County Alluvial Testing Complex and Site 22 locations south of Yucca Mountain has indicated that the alluvium behaves as an unconfined aquifer at shallow depths, and then transitions to a leaky-confined or confined aquifer system beneath the first significant confining layer. The results indicate that subhorizontal confining or semi-confining layers exist in the alluvium, but insufficient data exist to predict their depth and lateral extent as a function of location. Composite horizontal hydraulic conductivity estimates from cross-hole hydraulic testing in the alluvium are on the order of 2 to 5 m/day, with individual isolated zones having horizontal conductivities as high as 12 to 13 m/day.

Within the boundaries of the saturated zone model domain, there are several primary components that affect the local flow system and potential radionuclide transport.

The Solitario Canyon Fault is important because it could provide a vertical flow path from the surface to the saturated zone. However, depending on its conceptualization, it also acts as a barrier to flow that might otherwise travel from Crater Flat to Yucca Mountain.

Recharge to the saturated zone is important because it impacts the transport time of radionuclides that could escape from the repository. Flux from the steady-state stress period of the 2004 Death Valley regional flow system (Belcher 2004) provides boundary volumetric/mass flow rates for the site-scale model.

The three tuff units of the Crater Flat Group are likely to be among the more permeable hydrogeologic units near the repository and, thus, are the most likely paths for potential radionuclide transport.

The shallow alluvial aquifer in Fortymile Wash is important because it bounds the likely flow paths for water leaving the repository area, and also has higher retardation potential characteristics for many radionuclides.

The regional carbonate aquifer underlies the likely flow paths for water leaving the repository area. This aquifer also provides an upward gradient that keeps the flow paths shallow, and effectively isolates the local Yucca Mountain system from the regional carbonate aquifer.

The large, moderate, and small hydraulic gradients where radionuclides, if they originated from the repository, would be transported control the shallow flow field below and downgradient from the repository (SNL 2007b, Section 6.3.1).

Potentiometric Characteristics—The potentiometric surface generally implies a hydraulically well-connected flow system within the uppermost saturated zone. Within the saturated zone site-scale model area, 17 boreholes currently monitor or have historically monitored water levels in more than one vertical interval. Vertical head differences within the uppermost saturated zone are variable throughout the saturated zone site-scale model area. Of the 17 sites, 12 gradients are upward, and 5 are downward (BSC 2004d, Section 6.3.2).

The potentiometric surface in the Yucca Mountain site area (SAR Figure 2.3.9-11) is characterized by small gradients east and southeast of the site and in the Amargosa Desert. Moderate to large potentiometric surface gradients are observed west, south, and southwest of Yucca Mountain, and a large gradient occurs north of Yucca Mountain (BSC 2004d, Section 6.4).

Paleohydrologic Evidence for Past Water Levels—In the carbonate terrane of the eastern Amargosa Desert, evidence indicates that the late Pleistocene water levels in Devils Hole were 9 m higher than present. In the Amargosa River at the Nevada–California state line, within the Alkali Flat–Furnace Creek groundwater basin (Figure 5-41), late Pleistocene water levels reached more than 6 m above the present river channel. At the ridge dividing the Amargosa Valley and Crater Flat sections of the Alkali Flat–Furnace Creek groundwater basin, about 15 to 18 km south of the repository site, water levels reached 10 to 30 m above the present water table (BSC 2004a, Section 8.4).

Groundwater flow modeling of the regional flow system under projected future climate conditions simulated water levels of 60 m to 150 m higher than present beneath Yucca Mountain (D'Agnese et al. 1999, p. 2). Given a present-day water table at 730 m above sea level (Section 2.3.8.5.3), a flat water table at 850 m above sea level is expected to bound the potential effects of water table rise for the purposes of unsaturated zone flow. The water table elevation of 850 m results in a water table that is a minimum of 188 m below repository waste emplacement drifts because all repository drifts are at elevations of 1,038 m or higher (BSC 2007e). The design requirement for standoff of the repository waste emplacement drifts from the water table is a minimum of 120 m (SAR Section 1.9).

5.2.2.4 Present Climate and Controlling Influences

The nature of climate in the Yucca Mountain region is constrained by its location relative to local topography and controlled by changes in atmospheric circulation patterns. The Yucca Mountain region currently has a relatively arid climate, with annual precipitation totals ranging between approximately 100 and 250 mm/yr (DOE 2002b, Section 3.1.2.2). The present-day climate in the Yucca Mountain area is generally characterized by hot, dry summers, but occasionally monsoonal flow develops and thunderstorms occur, resulting in streamflow in the area. Winters are typically dry and cool, although El Niño conditions in the Pacific Ocean sometimes lead to increased winter moisture. Section 5.2.5 and SAR Section 2.3.1 provide further information about past climates and forecasts for climate states for the next 10,000 years.

5.2.2.5 Water Quality and Water Use

The quality of groundwater in the region is marginally suitable for agricultural use and, in most respects, is suitable for industrial uses and for potable drinking water. Notable exceptions to the latter are the fluoride and uranium content, which has exceeded state and federal limits in water wells at Beatty and Amargosa Valley (BSC 2004a, Section 8.5.3), and exceedance for arsenic at Beatty, Round Mountain, and Manhattan caused by the recent reduction in the drinking water standards for that element (Buqo 2004). As a result of an arsenic treatment system installed in 2006, J-12 and J-13 (the current supply wells for Yucca Mountain) are compliant with the arsenic drinking water standard (BSC 2007f).

Throughout the Death Valley regional flow system, groundwater is the principal source of water for agricultural, mining, industrial, municipal, and domestic uses. Surface water is sparsely distributed, and it occurs generally at small and unreliable rates of flow; therefore, it is a minor component of the regional water resource. In contrast, groundwater is widely available and has been sufficient to satisfy most of the historically modest demand. Most of the groundwater resource development in the central Death Valley subregion has occurred in Nevada, although minor development has taken place in the extreme southwestern Amargosa Desert near Death Valley Junction, California. In the Furnace Creek area of Death Valley National Park, spring discharge supplies the small domestic and commercial demand (BSC 2004a, Section 8.5.3).

Generally, groundwater can be obtained in sufficient amounts needed for use throughout the region. In the lowland valleys, including the Amargosa Desert, thick alluvial deposits in the valley-fill aquifer supply water to wells sufficient to irrigate the soils of the area. Wells at selected locations on the Nevada Test Site that tap into volcanic aquifers and the deep carbonate aquifer have furnished adequate water for the industrial needs of the Nevada Test Site. The carbonate aquifer, along with the alluvial aquifers, is widely viewed as a major water-supply source in southern Nevada (BSC 2004a, Section 8.5.3).

A study of groundwater withdrawals from the Death Valley regional flow system indicated a relatively consistent annual increase in the total groundwater withdrawal from 1944 (5,000 acre-ft) to 1998 (90,000 acre-ft) (Moreo et al. 2003, Figure 4). Withdrawals were categorized into three general classes: (1) mining, public supply, and commercial water use; (2) domestic water use; and (3) irrigation water use. Water-use categories were based on the method of estimating pumpage. Mining, public supply, and commercial wells typically were metered, and withdrawals ranged from 2% to 13% of annual withdrawals from the study area. Withdrawals for domestic water use, estimated as the number of domestic wells multiplied by a consumption rate, ranged from 1% to 7% of total annual withdrawals. Irrigation was estimated as the product of acreage and application rates and accounted for more than 80% of all withdrawals during any year (Moreo et al. 2003, p. 22). Annual pumpage from the Nevada Test Site averaged 1,300 acre-ft and increased significantly from 1970 to 1985. Annual water-use coefficients for the Nevada Test Site increased from 0.1 to 1.4 acre-ft per capita between 1961 and 1998 (Moreo et al. 2003, p. 9). Further information on groundwater withdrawals near Yucca Mountain and in the Amargosa Desert can be found in work by Fenelon and Moreo (2002) and Locke and La Camera (2003).

5.2.2.6 Water Budget

Water use studies in nearby areas suggest local mining of groundwater. For example, Fenelon and Moreo (2002, p. 1) reported that water levels in some parts of the Amargosa Farms area have been declining since the 1960s, when large-scale pumping began in the area. The Oasis Valley groundwater basin to the west of Yucca Mountain shows evidence of water-level fluctuations that correlate with variations in total annual groundwater withdrawal by the Beatty Water and Sanitation District, which is the largest single user (Reiner et al. 2002, p. 33). Although no recent water budget studies have been done in the immediate vicinity of the site, evidence suggests water levels have been stable during the period of measurement (BSC 2004d, Section 6.2.1). Recent task reports by the University of Nevada, Las Vegas, indicated that annual groundwater level variability for all wells in the periodic network is low. This supports conclusions based on existing analyses of long term monitoring data that water levels near the repository are remarkably stable.

An investigation of water withdrawals in the entire domain of the Death Valley regional flow system determined that water use on the Nevada Test Site fluctuated by as much as a factor of four, but was a very small percentage (about 1%) of the total water withdrawal in the basin. On the other hand, withdrawal in Pahrump and Amargosa Valley most likely increased steadily from 1945 until the present (Moreo et al. 2003).

Based in available data and estimates, the total water use in Nye County in 2000 was about 101,000 acre-ft. This is 13% higher than estimates of 1995 usage, but identical to the Nevada State Water Plan. The projections are that by 2050, the demand will be 252,000 acre-ft, almost 2.5 times the 2000 demand. Most of this increase is in Pahrump, and not associated with federal lands. Some increase in water use is estimated for Amargosa (Buqo 2004).

5.2.2.7 Surface Water Hydrology

Yucca Mountain is located in the Amargosa River drainage basin, which is a major tributary to Death Valley. The area drained by the Amargosa River and surrounding drainage system features is depicted in Figure 5-42. Streamflow from Yucca Mountain can extend from local drainages to the Amargosa River and then to Death Valley. The ephemeral stream channels of the Amargosa River and its tributaries rarely exhibit streamflow, except in direct response to precipitation, or for short distances where groundwater discharges at springs into the channel system. Water is lost to infiltration and evaporation as streamflow moves downstream. During infrequent flood events, flow occurs throughout the Amargosa River and has filled many square miles of the Death Valley salt pan to depths of 1 ft or more (BSC 2004a, Section 7.1.1).

Surface Stream Channels and Impoundments—The headwaters of the Amargosa River are on Pahute Mesa (Figure 5-42), and the river flows southward through Oasis Valley, where the flow largely infiltrates into stream deposits and is dissipated by evapotranspiration. The channel is then joined by Beatty Wash and passes through Amargosa Narrows into the Amargosa Desert. The channel trends southeasterly along the southwestern flank of the Amargosa Desert about 50 mi to Alkali Flat (also known as Franklin Lake Playa), where it passes through a bedrock narrows by Eagle Mountain to enter the Lower Amargosa Valley. The channel continues 40 mi farther south past the southern end of the Black Mountains, turns westward where it is joined by Salt Creek, and then enters Death Valley. The Amargosa River channel then extends northwesterly 50 mi, terminating at Badwater Basin, which contains the low point of Death Valley (BSC 2004a, Section 7.1.1.1).

The ephemeral stream channels on Yucca Mountain are tributary to Fortymile Wash, which begins on Pahute Mesa (Figure 5-42) and flows southward through Fortymile Canyon about 25 mi before flowing onto an alluvial fan at the narrows. Fortymile Wash spreads out into a distributary system in the Amargosa Desert and, during floods, joins the Amargosa River about 13 mi northwest of Death Valley Junction, California. An unnamed ephemeral stream channel in Crater Flat drains the western slope of Yucca Mountain via Solitario Canyon. This channel also collects drainage from the southern slope of Yucca Mountain, then drains to Windy Wash, which joins the Amargosa River near its confluence with Fortymile Wash. Topopah Wash drains Jackass Flats. Water from Topopah Wash flows into the Amargosa River during floods (BSC 2004a, Section 7.1.1.1).

The only permanent surface water bodies (impoundments) in the vicinity are Crystal Reservoir, Lower Crystal Marsh, Horseshoe Reservoir, and Peterson Reservoir, which are artificial impoundments that store spring discharge in Ash Meadows (Figure 5-42) about 50 km southeast of Yucca Mountain. Like the streams in the area, the playas shown in Figure 5-42 contain water only after periods of heavy precipitation. However, some, like Badwater Basin in Death Valley and Alkali Flat in the Amargosa Desert, represent sumps for groundwater discharge and can be wet for extended periods as the water evaporates (BSC 2004a, Section 7.1.1.1).

Streamflow—Surface water flows have been monitored at numerous sites in the Yucca Mountain region, and the nature of streamflow in the desert terrain of the Amargosa River basin is extremely erratic and sparse (BSC 2004a, Section 7.1.1.2). SAR Section 1.1.4 provides a discussion of flooding potential and probable maximum floods.

Flood History and Potential—The current major flood hazard at and near Yucca Mountain is flash flooding. Flash floods are the result of intense rainfall and surface runoff from localized convective storms, or from high-intensity precipitation cells within regional storm systems (BSC 2004a, Section 3.4.3.1). The geologic evidence found for prehistoric flooding in Coyote Wash (a tributary to Drill Hole Wash) on Yucca Mountain has been evaluated in trenches, excavated across and along the present-day channel, that exhibit sediments indicative of multiple flood events, including debris-flow deposits. Surficial boulders near the trenches were used to estimate the magnitude of the flood that deposited them during the Holocene period. Assuming all the boulders were emplaced by the same flood, a peak discharge of 68 m^3/s was estimated to have occurred in the north fork of Coyote Wash. The combined flows of the north and south forks could result in a peak flow as large as 142 m^3/s (BSC 2004a, Section 3.4.3.2).

A flood that occurred on February 24, 1969, is believed to have been the most severe flood in the Amargosa River basin during recent times. The peak flow on that date in Fortymile Wash was estimated at about 20,000 ft^3/s on the basis of channel geometry and residual evidence (observations of remnant high-water marks) discovered during a flood prediction study. About 80 mi^2 (50,000 acres) of the Badwater Basin salt pan in Death Valley were flooded to depths of as much as 3 ft, with a resultant lake volume of about 50,000 acre-ft. Fortymile Wash flowed on March 3, 1983, as a result of a regional rainstorm that may have melted some snowpack at the higher basin altitudes. Flow peaked at 570 ft^3/s, as recorded by the gauging station near Well UE-25 J-13, and at about 400 ft^3/s downstream at a gauging station near U.S. Highway 95. Other summer rainstorms caused flows in Fortymile Wash in 1984 and 1995, and winter conditions caused flow in 1992, 1993, 1995, and 1998 (BSC 2004a, Section 3.4.3.2).

5.2.2.8 Hydrologic Features and Processes Used to Estimate Postclosure Performance

Hydrologic FEPs included in the process and abstraction models developed for the TSPA are listed in tables presented in SAR Section 2.2. These FEPs include the following:

- Stratigraphy, fractures, faults, rock properties, and characteristics of faults and fractures
- Climate change, water table change, seepage into drifts under ambient conditions and thermal effects on seepage, flow characteristics, perched water characteristics, and colloid characteristics.

These features are used to establish the geometry and characteristics of flow paths for both unsaturated and saturated zone flow and transport models, and to develop seepage models. For assessing flow and transport properties, the unsaturated and saturated zone properties were characterized in relation to flow properties, flow pathways, unit and hydraulic properties, transport properties, and external influences, such as climate change. These properties are important to postclosure performance because they bound the rate at which released radionuclides may migrate to the accessible environment. SAR Sections 2.4.2.3.2.1.1 and 2.4.2.3.2.1.9 describe the unsaturated zone flow and transport components of the TSPA model. SAR Section 2.4.2.3.2.1.10 contains a description of the saturated zone component of the TSPA model.

5.2.2.9 Potential Hydrologic Hazards during the Preclosure Phase

A list of potential external hazards affecting preclosure performance has been developed (BSC 2008a, Section 4.4). Hazards associated with the postclosure period are addressed in the FEPs screening process (SAR Section 2.2.1).

Hazards associated with flooding have been evaluated. As described in SAR Section 1.1.4, the primary flooding hazard at and near Yucca Mountain occurs as a result of flash flooding, which is evaluated as a probable maximum precipitation event, and runoff resulting from that event. The procedure used for determining the probable maximum amount and duration of precipitation is discussed in SAR Section 1.1.4.3.1.

5.2.2.10 Developments in Hydrologic Data and Models during Site Characterization

The site characterization program resulted in significant improvements in the understanding of the major processes controlling water movement in the unsaturated zone. Information about conditions and processes in thick unsaturated zones in arid climatic settings was scarce prior to site characterization. Studies to determine the influence of topography and surface materials on infiltration provided important data to develop an infiltration model that could be used to simulate infiltration for a range of future climate conditions. Data and analysis to improve models of deep percolation to the repository horizon, and from the repository to the water table, were important, as was information to establish the extent of fracture–matrix interaction during unsaturated zone flow and transport. The role and importance of accumulation of perched water and lateral flow within the unsaturated zone were other key areas where testing resulted in improved models that included these processes.

Field experiments, theoretical analyses, and numerical modeling have greatly improved the understanding of seepage into waste emplacement drifts. Data that confirm the effectiveness of capillary diversion and other processes that reduce the amount of percolation flux entering the drifts as seepage represents some of the most important information gained during site characterization. This information has been used to develop the basis for predicting seepage into waste emplacement drifts under both ambient and thermal conditions.

Regional saturated zone models have been upgraded on the basis of improved information about recharge locations and amounts, specific discharge, and improved hydraulic property data. The regional-scale flow model provides boundary conditions for the site-scale saturated zone flow model. Results of site characterization testing have improved the basis for modeling the geochemical environment along saturated zone transport pathways. Improved data regarding the role of matrix diffusion, sorption, and colloid filtration on radionuclide transport rates are included in saturated zone models. The site-scale flow model was calibrated using water-level data, while additional observations from hydraulic field tests (temperature, hydrochemistry, and isotopic data) were used to provide further confidence in the model.

5.2.3 Geochemical Characteristics of the Yucca Mountain Site

Key geochemical attributes affecting the ability of the natural barrier below the repository to prevent or substantially reduce the rate of movement of radionuclides from the repository to the accessible environment include the following:

- Sorption capacities of the various geologic materials along potential flow paths
- Solubilities of the radionuclides present in the disposed waste materials
- Thermally induced geochemical and geomechanical changes or coupled processes expected to occur in the near-field environment
- Chemistry of fluids in contact with the waste package and drip shield.

Radionuclides that may be available for transport from the repository have varying retardation characteristics. Several radionuclides that are the dominant contributors to the total inventory are significantly retarded in the unsaturated zone when there has been significant fracture-matrix exchange by diffusion or advection. The sorption of these radionuclides that diffuse or advect into the matrix, in combination with radioactive decay, prevents the movement (or significantly reduces) the rate of movement of these radionuclides from the repository to the accessible environment. Sorption is included in the unsaturated zone radionuclide transport models that are presented in SAR Section 2.3.8.5.2.

Several radionuclides may be transported in the unsaturated zone. Retardation of a large fraction of the colloidally transported radionuclides is sufficient to prevent the movement, or significantly reduce the rate of movement, of these radionuclides from the repository to the accessible environment. A small fraction of the colloids are transported unretarded in the unsaturated zone. Sorption of colloidal transport of radionuclides is included in the unsaturated zone radionuclide transport models presented in SAR Section 2.3.8.5.2.

Several radionuclides that are the dominant contributors to the total inventory may be significantly retarded in the saturated zone. The sorption behavior of these radionuclides either prevents (or substantially reduces) the rate of movement of radionuclides in the saturated zone from the repository to the accessible environment. Other radionuclides are slightly sorbed. Radionuclide sorption and mineral precipitation effects are presented in SAR Section 2.3.9.3.2.2.

Several radionuclides may be transported colloidally in the saturated zone. These colloids can be filtered and retarded as they are transported through the fractured rock mass and porous alluvium. Colloid facilitated transport in the saturated zone is presented in SAR Section 2.3.9.3.2.3.

The geochemistry of the unsaturated and saturated zones and the geochemistry and coupled processes occurring in the near-field and in-drift environments are summarized in this section.

5.2.3.1 Hydrochemistry of Unsaturated and Saturated Zones

Unsaturated Zone Hydrochemistry—Characteristics of pore waters extracted from unsaturated core samples indicate a wide range of water compositions, ranging from calcium-chloride-type or calcium-sulfate-type waters to sodium-bicarbonate-type waters. Measured water compositions derived from pore waters are depicted in a Piper diagram shown in SAR Figure 2.3.5-5, and are discussed in SAR Section 2.3.5.3. In general, the pore waters from the TSw unit have equal quantities of sodium and calcium. The dominant anion is bicarbonate, with a much smaller proportion of sulfate than typical PTn unit waters. In terms of relative proportions of anions, the chemical composition of pore waters from the TSw unit is intermediate between those of the PTn and CHn units. Pore waters extracted from the CHn unit are sodium carbonate-bicarbonate type waters; within the CHn unit, sodium concentration increases with increasing depth. This shift is because of zeolites preferentially sorbing calcium and magnesium while releasing sodium to the water. These sorption processes are also expected to operate on any cationic radionuclides, such as cesium and strontium, that are released into aqueous solutions and migrate into the zeolitic CHn unit. Deviations from vertical trends in ion concentrations, including those of chloride, sulfate, and sodium, indicate at least some component of lateral flow within the nonwelded units (BSC 2004a, Section 5.2.2.4).

Perched water bodies in the unsaturated zone beneath Yucca Mountain may have implications for flow and transport in the unsaturated zone. Smaller concentrations of chloride in perched water indicate that pore waters and perched waters have distinctly different histories of geochemical evolution, reflecting different degrees of evaporation or water–rock interaction (BSC 2004a, Section 5.2.2.4.2). There are several explanations for the difference between chloride concentrations in perched and pore waters (BSC 2004a, Section 7.9.1.3). One explanation is that the perched water was derived from fracture water that is more dilute than water in the rock matrix. Another explanation is that the perched water was derived from areas of higher infiltration and lower chloride. These hypotheses for the origin of perched water are not mutually exclusive (BSC 2004a, Section 5.2.2.4.1). The mechanism proposed to explain the chemical differences in pore waters and perched waters is one in which pore waters flow primarily through the rock matrix, whereas perched waters accumulate from flow that occurred primarily through the fractures in the host rock. However, the absence of a clear bomb-pulse signal for any of these radionuclides in perched water samples indicates that the flux of water from the surface downward through fractures to perched water bodies must be small (BSC 2004a, Section 5.2.2.8). Chloride concentration data indicate that perched water was derived mainly from fracture flow, with only a small degree of interaction with matrix water (BSC 2004a, Section 7.9.1.3).

Saturated Zone Hydrochemistry—Saturated zone hydrochemical data were collected and analyzed to support the conceptual understanding of groundwater flow paths. In these analyses, flow paths were qualitatively evaluated in the context of the spatial distribution of hydrochemical and isotopic concentrations, including chloride and sulfate and the oxygen and hydrogen isotopic ratios, $\delta^{18}O$ ($^{18}O/^{16}O$) and δD (D/H), respectively (SNL 2007b, Appendix A, Section A6.3.1.2).

Flow paths derived from hydraulic analyses are compared to flow paths deduced from the hydrochemical data shown in Figure 5-44 (SNL 2007b, Figure 7-5). These flow paths must be evaluated in the context of the hydraulic gradient while considering the possibility that flow paths can be oblique to the potentiometric gradient because of anisotropy in permeability. These flow paths were drawn by first using chemical and isotopic constituents generally considered to behave conservatively in groundwater, such as chloride (Cl^-) and sulfate ($SO_4{}^{2-}$) ions. However, because no single chemical or isotopic species varies sufficiently to determine flow paths everywhere in the study area, multiple lines of evidence were used to construct the flow paths. This evidence includes the areal distribution of chemical and isotopic species, sources of recharge, groundwater ages and evaluation of mixing/groundwater evolution through scatter plots, and inverse mixing and reaction models (SNL 2007b, Appendix A).

As shown in SAR Table 2.3.9-7, for most constituents two water compositions approximately bracket the compositions of waters, both in the tuff units and alluvium, along the potential flow paths to the accessible environment. One is typified by water from well UE-25 J-13 (J-13), located on the east side of Fortymile Wash. The other is from well UE-25 p#1, located near the southern entrance to the ESF. Well J-13 is pumped from volcanic units (Topopah Spring Tuff), whereas UE-25 p#1 water is pumped from the carbonate aquifer. The J-13 and UE-25 p#1 waters were used in sorption experiments as end-member compositions intended to bracket the impact of water composition on sorption coefficients (SAR Section 2.3.9.2.2.5).

5.2.3.2 Radionuclide Transport in the Unsaturated and Saturated Zones

Groundwater flow is the predominant transport mechanism in the unsaturated zone. Where fracturing is more prevalent, such as in the welded units, advection in the fractures (fracture flow) is expected to be the dominant transport mechanism. Fracture-dominated advective transport would be expected to lead to the earliest radionuclide arrivals at the water table because of fast water flow, and would also be expected to reduce the potential for retardation by limiting both diffusion into the matrix and immobilization by means of solute sorption or colloid filtration in the matrix (SNL 2007k, Section 6). Both dissolved and colloid-facilitated transport properties and mechanisms for the unsaturated zone and saturated zone are discussed in further detail in SAR Sections 2.3.8 and 2.3.9, respectively.

In zones dominated by fracture flow, radionuclide transport is affected by interactions between fractures and matrix. The diffusion of radioactive solutes into the rock matrix can be an important retardation mechanism controlling the radionuclide transfer between the fractures and the rock matrix, and it is the only significant retardation mechanism for nonsorbing solutes, such as ^{99}Tc. In the process of matrix diffusion, radionuclides move into the matrix, where water flow is slow and where sorption or filtration is much more likely to occur because of greater contact areas and longer contact times between water and rock. Matrix diffusion removes some radionuclides from the flowing fractures, thus slowing radionuclide transport (SAR Section 2.3.8.3).

If radionuclides are released in the aqueous phase from the emplacement drifts and migrate through the unsaturated zone as dissolved species, or are sorbed onto colloids, they will enter the groundwater flow regime in the saturated zone. The two functions of the saturated zone, which are the ability to delay the arrival and attenuate the radionuclides via the mechanisms of dispersion, diffusion and sorption, have been demonstrated in the saturated zone transport model (SNL 2008c, Section 6.8.6). The transport of radionuclides as solutes in the saturated zone will be affected by advection, diffusion, dispersion, and, for reactive radionuclides, sorption. The effect and importance of these processes differ in the fractured tuff units and the porous alluvium (SNL 2008c, Section 6.8). In fractured tuffs, advective transport occurs predominantly within fractures;

therefore, the fracture porosity, referred to as flowing interval porosity, is important for describing the advective velocity. Major flowing fracture zones are generally spaced on the order of meters to tens of meters apart. In the alluvium, advective transport occurs through the pore space. Because the effective porosity of the alluvium is considerably greater than the flowing interval porosity in the fractured tuff, the transport velocity in the alluvium is reduced (SNL 2008c, Section 6.4.2).

Longitudinal dispersion causes some radionuclides to migrate either faster or slower than the average velocity along the groundwater flow trajectory. Horizontal and vertical transverse dispersion causes solute plumes to widen horizontally and vertically over time and distance. Both longitudinal and transverse dispersion result in reduced concentrations at any given point within a solute plume relative to the concentration that would be present in the absence of dispersion (SNL 2008c, Section 6.5).

5.2.3.2.1 Solubilities of Key Radionuclides

Dissolved concentrations of radionuclides in water moving away from the emplacement drifts can be limited by three mechanisms (BSC 2004a, Section 5.3.2.1):

- Slow dissolution rates of waste form solids
- Solubility of individual radionuclides
- Sorption of the radionuclides onto geologic media.

Section 5.2.3.2.2 summarizes radionuclide sorption properties related to the Yucca Mountain environment.

The approach used to establish solubility limits for the radionuclide elements included in the TSPA is described in SAR Section 2.3.7.10. A thermodynamic database and a geochemical modeling tool, supplemented by laboratory tests, are used to establish solubility limits for the water chemistries that are expected within the waste packages. Sensitivity studies show that solubilities are most sensitive to pH, $f\mathrm{CO}_2$, and fluoride concentration. The thermodynamic equilibrium computer code EQ3NR and a thermodynamic database are used to produce solubility limits considering the controlling solid phases, water chemistry, and temperature (SNL 2007l). Table 2.3.7-2 (SAR Section 2.3.7.10) provides a list of results of the screening analysis for radionuclides that are most important to potential dose.

5.2.3.2.2 Radionuclide Sorption in the Saturated and Unsaturated Zones

Sorption describes a combination of chemical and physical interactions between dissolved radionuclides and the solid phases. Sorption removes a portion of the dissolved species from the liquid phase and transfers it to the solid phase. The solid phase includes the immobile rock matrix, immobile colloids, and mobile colloids. Sorption onto the matrix or immobile colloids results in retardation of radionuclide transport, while sorption onto mobile colloids can enhance radionuclide transport. Although these reactions can be complex, they typically are represented in transport calculations by a constant, which is the sorption distribution coefficient K_d (SNL 2007k, Appendix A).

On the basis of laboratory testing, radioisotopes of iodine, technetium, and carbon are assigned a K_d value of zero, which means that these radionuclides do not sorb. Other radioisotopes, such as uranium, neptunium, plutonium, cesium, and americium, have moderate to large sorption coefficients. SAR Table 2.3.8-2 provides sorption coefficients for 11 radioisotopes (uranium, neptunium, plutonium, americium, protactinium, cesium, strontium, radium, thorium, selenium, and tin). Fracture sorption processes are not considered in the site-scale transport model because of the high degree of uncertainty in the distribution and amounts of sorbing minerals on fracture surfaces.

Sorption properties of tuff and alluvial materials have been studied in laboratory and field tests. Comparison of laboratory and field observations generally confirm that the use of laboratory-derived sorption parameters reliably predicts field-scale radionuclide transport (SNL 2007a, Sections 6.3 and 6.5). For tuff, it is apparent that the lithium K_d values deduced from the field tracer tests (assuming any given lithologic unit) are consistently larger than the corresponding K_d values measured at the lowest lithium concentrations in the laboratory. A likely explanation for this result is that the lithium in the field tests came into contact with mineral surfaces that were not present or were under-represented in the small-scale laboratory tests. These results suggest that the use of laboratory-derived K_d values to predict sorbing species transport in the saturated fractured tuffs near the C-Wells location would tend to under-predict the amount of sorption experienced by the species in the field (SNL 2007a, Section 6.3.6), and therefore over-predict the transport of these species to the biosphere.

Lithium sorption parameters obtained in laboratory and field tests in alluvium also were compared to the results of C-Wells tracer testing. For alluvium at MW-22S, although the laboratory data set is limited compared to that for the Alluvial Testing Complex, the results suggest that apparent lithium sorption was greater in the field tracer test than in the laboratory batch tests (SNL 2007a, Section 6.5.7).

Increased temperature will affect the precipitation of new phases, the generation and stability of colloids, and the overall aqueous geochemistry of the drift and near-field environments. Measured sorption coefficients onto tuffs were found to be higher at elevated temperatures for americium, barium, cerium, cesium, europium, plutonium, strontium, and uranium. Consequently, for a given water and mineral composition, sorption coefficients measured at ambient temperatures should be generally conservative when used to describe the aqueous transport of cationic species, even at elevated temperatures (BSC 2004a, Section 5.3.3.7).

5.2.3.3 Colloid-Facilitated Transport

Radionuclides can undergo colloid-facilitated transport in both the tuffs and the alluvium. Colloids reduce the interaction of radionuclide species with the rock matrix, and allow for greater mass flux than could transport as aqueous species alone. Because of their size, larger colloids can only move through the center of pores and fractures where velocities are larger than the average water velocity, leading to greater transport velocities for larger colloids. The larger colloids cannot penetrate into the matrix from the fractures because of size exclusion. Thus, the colloid mass in the fractures is not significantly reduced through colloidal diffusion or hydrodynamic dispersion; therefore, practically all of it moves exclusively through the fractures (SAR Section 2.3.9.3.2.3).

Radionuclide-bearing colloids transported to the saturated zone may include natural colloids, typically clay or silica; waste-form colloids resulting from degradation of spent nuclear fuel or high-level radioactive waste; and iron oxyhydroxide colloids resulting from degradation of the waste package. Radionuclides may be reversibly or irreversibly sorbed to colloids. For example, plutonium and americium are typically 90% to 99% irreversibly sorbed. Experimental studies suggest that waste form colloids, such as hematite, pose the greatest risk for colloid-facilitated transport. However, these colloids have to migrate through the waste package, invert, and unsaturated zone before reaching the saturated zone in order to make a significant contribution to doses. Test results also indicate that clay colloids are likely to facilitate plutonium or americium transport in the saturated zone to a greater degree than silica colloids in the saturated zone (SAR Section 2.3.9.3.2.3).

5.2.3.4 Near-Field and In-Drift Chemistry and Hydrology

The chemical composition of pore water within the rock units above and at the repository horizon may influence the composition of potential future seepage water that could come into contact with the drip shield and waste packages. Therefore, data obtained regarding ambient chemical composition of these pore waters and perched waters help bound the range of seepage water compositions that are used in coupled chemical process analyses.

5.2.3.4.1 Coupled Processes in the Near-Field Environment

Emplaced nuclear waste generates heat that can affect the near-field environment. The objective of the thermal testing program was to gain a more in-depth understanding of the coupled thermal, hydrologic, mechanical, and chemical processes. Satisfaction of this objective led to a better understanding of how thermally driven coupled processes would affect the performance of the waste packages and the flow and transport of radionuclides in the EBS and natural systems (and consequently, the performance of the repository). The field tests that investigated thermal-hydrologic-mechanical-chemical behaviors were the Large Block Test, the Single Heater Test, and the Drift Scale Test.

The Large Block Test is located in Fran Ridge, southeast of Yucca Mountain. The heating phase of the Large Block Test started in February 1997 and continued until March 1998, at which time the heaters were turned off. Cooling-phase measurements at the Large Block Test were made until September 1998. Upon completion of the postcooling characterization of the Large Block Test block, a final report was prepared (Lin et al. 2001).

The Single Heater Test, located in Alcove 5 of the ESF, started in August 1996 and continued for 275 days until May 1997. The cooling phase continued until January 1998, at which time postcooling characterization of the test block commenced.

The Drift Scale Test is also located in Alcove 5 of the ESF. The results from characterizing the test block are contained in *Ambient Characterization of the Drift Scale Test Block* (CRWMS M&O 1997c). The heating phase of the Drift Scale Test started in December 1997 and lasted approximately 4 years until January 14, 2002. The cooling phase started January 14, 2002, and lasted until December 31, 2005, when most of the measurement ceased. Drift Scale Test measurements through the entire 8-year period are presented in the *Thermal Test Measurements Report* (SNL 2007d).

Coupled processes in the repository environment are relevant to repository performance because they may affect the chemical environment for corrosion of the drip shield or waste package and mobilization of radionuclides. The processes that affect radionuclide transport in the EBS and the host rock are addressed in SAR Sections 2.3.7 and 2.3.8, respectively. To evaluate the effects of coupled processes, thermal, hydrologic, mechanical, and chemical models were developed and are described in SAR Sections 2.3.3 and 2.3.5.

The validity of coupled-process models was evaluated, in part, by comparing simulated results with the results measured during the Drift Scale Test (SAR Sections 2.3.3.3.2, 2.3.5.2, 2.3.5.3, and 2.3.5.4), which was performed in the ESF. Nine electrical floor canister heaters were placed in a drift to simulate radioactive-waste-bearing containers. Secondary (wing) heaters were placed in a series of horizontal boreholes drilled outward from the central axis of the heated drift. These heaters were intended to simulate the effect of adjacent emplacement drifts. The Drift Scale Test heaters were in operation for just over 4 years and then switched off. Since that time, the rock volume impacted by the test has been slowly cooling. Data on the evolution of gas-phase composition and aqueous speciation, isotopic composition, mineralogical alterations and associated porosity and permeability changes, pH evolution, changes in water content and air permeability, and rock deformations were collected during this test. The Drift Scale Test provided important data for studying the coupled processes in the repository environment (SAR Section 2.3.2.3.2.5).

5.2.3.4.2 Thermal-Hydrologic-Chemical Processes

The chemical evolution of waters, gases, and minerals is closely coupled to the thermal-hydrologic processes, which are boiling, condensation, and drainage. The distribution of liquid water determines where mineral dissolution and precipitation can occur, and where direct interaction, via diffusion, can occur between matrix pore waters and fracture waters. Evaporation tends to concentrate aqueous species in solution, whereas mineral precipitation and ion-exchange reactions may deplete individual chemical components.

The effects of thermal-hydrologic processes on water chemistry are varied and depend on the behavior of the dissolved species. Conservative species (i.e., those that are unreactive and nonvolatile), such as chloride, become concentrated in waters undergoing vaporization or boiling but are essentially absent from the vapor condensing in the fractures. Therefore, the concentration of conservative species in the draining condensate waters is determined by mixing with fracture water and diffusive mixing with matrix pore waters. Concentrations of aqueous species, such as calcium, are also affected by calcite dissolution or precipitation, as well as by reactions involving calcium-bearing zeolites, clays, and feldspar (SNL 2007m, Section 6.2.1.2).

Zonation in the distribution of mineral phases can occur as a result of differences in mineral solubility as a function of temperature. The inverse relationship between temperature and calcite solubility (as opposed to the silica phases, which are more soluble at higher temperatures) may result in zonation in the distribution of calcite and silica phases in both the condensation and boiling zones. Silica precipitation is likely to be confined to a narrower zone where evaporative concentration from boiling exceeds its solubility. In contrast, calcite could precipitate in fractures over a broad zone of elevated temperature, and where CO_2 has exsolved, because of temperature increases or boiling. Alteration of feldspars to clays and zeolites is likely to be most rapid in the boiling zone because of their increased solubility at higher temperatures (SNL 2007m, Section 6.2.1.2).

SAR Sections 2.3.5.4 and 2.3.5.5 provide additional discussion of thermal-hydrologic-chemical processes and modeling approaches.

5.2.3.4.3 Thermal Hydrology in Repository Host Rock

Thermal-hydrologic behavior in the near-field host rock is directly related to the spatial extent of boiling temperatures. The boiling point of water occurs at approximately 96°C at the elevation of the repository. Although evaporation, water vapor flow away from the heat source, and condensation occur at temperatures below boiling, significant rock dryout and reduction in relative humidity do not occur until the local temperature exceeds the boiling point of water (SNL 2008d, Section 6.1.3).

Because the majority of the heat during the preclosure period is removed through ventilation, rock temperature at the drift wall does not reach the boiling point of water during this time period (SNL 2008d, Section 6.1.3). The rock surrounding the drift will begin to dry out during the preclosure phase because the relative humidity of the ventilation air will be low compared to that in the rock pore space. At closure, when forced ventilation stops, the rock temperature increases and a dryout zone continues to expand in the rock around each emplacement drift (SNL 2008d, Section 6.1.3). After the drift wall temperature cools below the boiling point of water and liquid water can enter the drift, capillary diversion causes liquid to flow away from the drift opening (SAR Section 2.3.3). The contribution of condensate to seepage is limited because the bulk of the condensate flows through the pillars thus bypassing the drifts (SNL 2008d, Section 6.1.3.). The intensity of gravity flow is directly related to heat output, which will be strongest early in the thermal period when the dryout zone has its greatest extent. Gravity flow during the boiling period will be distant from the drift openings, and will decrease as the waste package heat output declines, and, therefore, will not contribute to seepage into the drifts (SAR Section 2.3.3.3).

Coupled thermal-hydrologic-mechanical processes in the fractured rock around a drift can affect the spatial distribution of percolation flux through stress-induced changes in porosity, permeability, and capillary pressure. Stress-induced changes occur initially as a result of tunnel excavation and heating of the rock in response to waste emplacement. Tunnel excavation affects the permeability through opening or closing of existing fractures and, potentially, through the formation of new fractures near the drift wall. After waste emplacement, heating of the rock mass induces thermal expansion and associated thermal stresses that alter the fracture permeability. Permeability changes that occur during the thermal period are reversible under some circumstances; however, given the general inelastic behavior of fractures, permanent residual changes in permeability will occur (SAR Section 2.3.5.2) (BSC 2004k, Section 6.1).

Mineral precipitation and dissolution in the fractures and matrix modify the porosity, permeability, and hydrologic properties of the host rock. Amorphous silica and, to a lesser extent, calcite are volumetrically the most important minerals that are expected to precipitate. The solubility of amorphous silica and other silica phases increases with temperature, so precipitation of these phases tends to be confined to a narrow zone where evaporative concentration exceeds the solubility (SAR Figure 2.3.5-13). Calcite is less soluble at higher temperatures, and tends to precipitate over a broad range of elevated temperatures and where CO_2 has exsolved because of temperature increases or boiling (SNL 2007m, Section 6.2.1.2). The rock mass changes due to mineral precipitation and dissolution are expected to be small in comparison to overall rock mass in the vicinity of the repository.

5.2.3.4.4 In-Drift Chemistry

The chemistry of water and gases present in the host rock directly affects the range of water compositions that are expected to develop in the drift environment during and following waste package emplacement. Geochemical conditions in the matrices of the host rock units and overlying rock formations, in fractures, in lithophysal cavities, and in breccia zones in these rock units will also exert a control on the evolution of the geochemical environment. The environment on the surfaces of the drip shield and waste packages at any point in time will control the nature and rate of corrosion processes. Additionally, the chemistry of fluids and seepage waters that may accumulate in the drift invert could influence the transport of constituents that might be released from the waste packages.

The in-drift chemical environment will evolve through three general stages: dryout, transition, and low temperature. Dryout will occur immediately after permanent closure, when the near-field rock temperature increases above the boiling point of water. During dryout, no seepage will occur because of vaporization and capillary diversion effects in the host rock surrounding the drift. Although seepage and condensation on the drift walls will not occur, deliquescence (acquisition of moisture from the surrounding atmosphere) of dust deposits on the waste package and drip shield may produce very small quantities of brines. The results of geochemistry testing indicate three brine types: calcium chloride brine, carbonate brine, and sulfate brine. Nitrate will comprise a large component of the more concentrated brines. With respect to the water types described above, nitrate behaves similarly to chloride (SNL 2007e, Section 6.13.5.3). When seepage water drips onto the drip shield or waste package surfaces, it may flow downward over the metal surface. When water is moving and significant evaporation occurs, spatial separation of components is possible, with transport of the more soluble aqueous components leaving behind less soluble precipitates. This process may affect the relative concentrations of NO_3^- and Cl^-, as halite (NaCl) may precipitate while more soluble nitrate salts remain mobile (SNL 2007e, Section 6.13.6).

The transition stage will occur as the host rock temperature cools to below the boiling point of water, and as the waste package temperature cools to below approximately 105°C. Vaporization will no longer prevent seepage, but capillary diversion will remain active. Evaporative concentration of any water that drips onto the waste package surface may occur during this phase. Estimated seepage water chemistries are analyzed over a range of discrete temperatures to determine the evaporative chemistries that may contact the waste package and drip shield surfaces during the transition stage (SAR Section 2.3.5.5). After the transition period, the low-temperature (postboiling) stage will persist through the remainder of the regulatory compliance period, including a return to ambient conditions. Capillary diversion will remain effective, and relative humidity within the drift will increase, approaching 100%. Higher humidities and lower temperatures will produce progressively more dilute brines on the waste package and drip shield surfaces.

SAR Sections 2.3.5.4 and 2.3.5.5 provide additional information on the in-drift physical and chemical environment.

5.2.3.5 Geochemical Processes and Features Used to Estimate Postclosure Performance

SAR Section 2.2 tabulates the complete set of FEPs that are included in the models supporting the TSPA. Those features and processes that depend on the geochemical characteristics of the rocks and water are briefly described in this section.

Geochemical Conditions and Processes in the Natural Barriers—Stratigraphic information for the Yucca Mountain site includes the chemistry and mineralogy of the rock units that contain potential radionuclide transport paths in both the unsaturated and saturated zones. Some minerals along fractures or in the rock matrix may offer the opportunity for sorption of radionuclide species. The presence of complexing agents, such as colloids, may also influence radionuclide transport. Molecular diffusion in response to chemical gradients is considered in modeling radionuclide transport. Chemical characteristics of both unsaturated and saturated groundwater that are included in process models include pH, Eh, ionic strength, and major ionic concentrations, all of which may vary spatially along the flow and transport pathways. Chemical characteristics of unsaturated zone groundwater are important as a starting point for estimating repository thermal effects on water chemistry. Chemistry of water entering the emplacement drifts is an attribute that is used to determine in-drift chemistry and its effects on engineered components. These features and processes are used to provide the geochemical parameters for process and abstraction models supporting the TSPA.

Geochemical Conditions and Processes in the Engineered Barriers—Chemical characteristics of water entering the emplacement drifts will be influenced by interactions with engineered materials, including steel or other materials used for supporting the tunnels. The chemistry (pH and dissolved species) of water entering the waste package influences dissolution rates and transport of radionuclides from the waste packages. Reduction–oxidation potential in the emplacement drifts influences the oxidation of in-drift materials and the solubility of radionuclide species. The kinetics of the dissolution and precipitation reactions occurring in the drift environment are important in predicting radionuclide transport. Colloids, including pseudocolloids formed from host-rock materials or corrosion products, may bind or sorb radionuclides, making them available for transport. The presence of chemical gradients may also contribute to diffusive transport of radionuclides, including those bound or sorbed to small colloidal particles. SAR Section 2.3.7.12 provides further discussion about the transport properties of the colloids in the repository environment.

Thermal effects on chemistry in the waste packages and emplacement drifts are also included in models to ensure water chemistry changes during the thermal period are evaluated. SAR Section 2.4.2.3.2.1.4 describes the TSPA integrated approach to representing the EBS chemical environment.

5.2.3.6 Developments in Geochemical Data and Models During Site Characterization

Early site investigations provided data on chemistry and mineralogy of rock units, as well as hydrochemistry of the saturated zone groundwaters. As a result of site characterization studies, an improved site model was developed that portrays the spatial distribution of zeolitized and vitric zones in rock units that contain potential radionuclide transport pathways. Characterization of the hydrochemistry of unsaturated zone groundwater was more challenging because of the difficulty of extracting and analyzing pore waters representing in situ conditions. As the design for the engineered systems evolved, thermal effects on water and rock chemistry were emphasized. In particular, bounding the range of pH and chemical constituents in ambient seepage water was important as a starting point for predicting changes in water chemistry due to thermal effects and interactions with engineered materials. Bounds for the chemistry of waters on the surfaces of the waste packages and drip shields were developed for predicting the performance of the Engineered Barrier System. Iterative performance assessments allowed prioritization of sorption experiments to focus on those radionuclide species most relevant to postclosure performance.

5.2.4 Overview of Geotechnical Properties of the Yucca Mountain Site

This section presents an overview of the geotechnical properties and conditions for both surface and underground rock materials. Geotechnical properties of surface materials are characterized for use in design studies. Geotechnical information is used to determine the potential for mechanical disruption of EBS features because of drift collapse caused by seismic events or time-dependent degradation of the rock mass. Site-specific characteristics of the rock units of the Topopah Spring Tuff that constitute the host rock at the repository horizon have been examined through geologic mapping and analysis of samples in surface exposures, and in surface-based boreholes and tunnels, alcoves, niches, and boreholes in the ESF and in the ECRB Cross-Drift. Laboratory testing of rock cores and in situ testing to obtain data at a larger scale provided the database used for repository design and the TSPA. SAR Section 1.1.5 provides further discussion of the geotechnical properties used for design of repository surface facilities. SAR Section 2.3.4 provides discussion of the results of geotechnical analysis related to mechanical disruption of the EBS.

5.2.4.1 Geotechnical Investigations

Because of the types of data, the method and location of data collection, and how these data are used, geotechnical properties and conditions are best described in the context of (1) the near-surface materials associated with the repository surface facilities and (2) subsurface material associated with the rocks that comprise the repository host horizon. However, there is some overlap between these two types of data. The locations of the explorations are shown in Figure 5-6. Subsurface conditions have been studied through site characterization, or inferred from geologic mapping, borehole data, and geophysical surveys. Geologic mapping has been performed for natural and excavated ground surfaces (trenches, pits, washes, and pavement surfaces) and in tunnels. Geophysical investigations include downhole spectral analysis of surface waves, vertical seismic profiling, reflection, refraction, and gamma-gamma surveys.

Repository host rock consists of the welded crystal-poor Topopah Spring Tuff, which is composed of the following four generalized zones, in descending order: upper lithophysal, middle nonlithophysal, lower lithophysal, and lower nonlithophysal (Tptpul, Tptpmn, Tptpll, and Tptpln, respectively) (BSC 2007a, Figure 6-5). Table 5-3 and Figure 5-30 contain a schematic of the various nomenclatures used to describe rock units at Yucca Mountain. From an engineering perspective, there are two general categories of host rock: nonlithophysal and lithophysal, based on the relative proportion of lithophysal cavities. The nonlithophysal zones are generally hard, strong, fractured rocks with matrix porosities of 10% or less. Fractures that formed during the cooling process are the primary structures in these zones. In contrast, the lithophysal zones have significantly fewer fractures of significant continuous length (i.e., trace length greater than 1 m), but have relatively uniformly distributed porosity in the form of lithophysal cavities. Lithophysal porosity in the lithophysal zones is on the order of 10% to 30% by volume (BSC 2007a, Section 6.1.3.2). Lithophysal rocks comprise approximately 85% of the waste emplacement area.

Surface and near-surface geotechnical properties and conditions at or near the location of the repository surface facilities were investigated using geologic mapping, boreholes, test pits, geologic trenches, and geophysics. Descriptions of geologic and geophysical investigation techniques and results are provided in *Geotechnical Data for a Potential Waste Handling Building and for Ground Motion Analyses for the Yucca Mountain Site Characterization Project* (BSC 2002a, Section 6).

The location of the surface facilities is underlain by alluvium that is mostly Quaternary in age, and deposited on a sequence of nonwelded and welded tuffs. The alluvium thickens to the east from 0 ft thick along Exile Hill to more than 120 ft thick on the eastern side of the area. Structurally, the area is crisscrossed with mostly high-angle normal faults of various separations. A north-northwest-trending normal fault, cutting across the northeastern edge of the surface facilities site, referred to as the Exile Hill Fault splay, has produced significant down-to-the-northeast separation of the volcanic stratigraphy. As a result, the area to the northeast of the Exile Hill Fault splay is characterized by a significantly thicker sequence of nonwelded bedded tuffs than is found to the southwest (BSC 2002a, Section 6.6.2).

5.2.4.2 Engineering Properties of Soil and Rock

This section provides brief summaries of the engineering properties of the soil and rock at the repository, with cross-references to sections where further information is available. Principal geotechnical material properties include the following:

- Static properties: strength and deformation characteristics
- Dynamic properties: shear modulus and material damping ratio as functions of shear strain
- Thermal properties: thermal conductivity, specific heat, and coefficient of thermal expansion.

The thermal properties are relevant only for the rock surrounding the emplacement drifts where significant temperature changes will occur. The shear-wave velocity profile of the site is also a relevant input to ground motion analysis. As discussed below, density and porosity are used to estimate other properties, such as strength, deformation characteristics, dynamic properties, and thermal properties.

5.2.4.2.1 Soil Material Properties for Surface Facilities

This section addresses the properties of coarse and granular alluvial deposits and colluvial deposits, valley fill, and both welded and nonwelded tuffs present at the location of the surface facilities.

Numerical values for geotechnical properties are discussed and presented in SAR Section 1.1.5.3. For the site response analysis of the surface geologic repository operations area, two materials were modeled: tuff and alluvium. Uniform values of total density were adopted for the tuff and alluvium. A value of 1.80 g/cm^3 for alluvium is adopted for input into the site response analysis, based on an evaluation of the measured data. For tuff, the same density used for the subsurface facilities, 2.2 g/cm^3, is adopted. SAR Section 1.1.5.3 also provides information about the following geotechnical properties: seismic velocities, density, shear strength of alluvium, Poisson's ratio, and dynamic shear moduli and damping ratios, which are briefly described in the following paragraphs.

Seismic Velocity Profile—Shear-wave and compression-wave velocities were obtained from downhole seismic and suspension seismic investigations. In addition, a surface-based method of characterizing velocity—spectral analysis of surface waves—was applied. Results from these efforts were used to develop seismic velocity profiles for the site (SAR Section 1.1.5.3).

Density and Relative Density—The total density of subsurface materials for surface facility design has been determined from gamma-gamma logging in selected boreholes. In situ and laboratory density tests have been performed on alluvial and colluvial deposits using several methods, including water-replacement tests, sand-cone tests, and nuclear tests (BSC 2002a, Section 6.8.3; BSC 2002b, Attachment I.2.2.1, Section 6.2, modified to include earlier tests). Relative densities for the alluvium and colluvium average 64% (1σ ranges from 45% to 82%), indicating the sandy gravel soil is medium dense to dense.

Shear Strength and Friction Angle of Alluvium—The shear strength of the alluvium at the site was evaluated using correlations of shear strength to relative density. The mean value of relative density, using this method, was 68%, and the mean value −1σ was 47%. Different correlations of friction angle with relative density have been developed by various researchers over the last several decades. Using Meyerhof's correlation for gravelly sand, the friction angle corresponding to the mean value of relative density is approximately 47°, and the friction angle corresponding to the mean value −1σ is 42°. Other correlations will yield other estimates of friction angle. Based on consideration of several correlations, a friction angle on the order of 39° is used as the value for the upper alluvium. Based on the beneficial effects of aging, the shear strength may tend to increase with depth (BSC 2002b, Section I.2.2.1).

Poisson's Ratio—Shear-wave and compression-wave velocities are used to calculate small-strain Poisson's ratio using the theory of elasticity. SAR Section 1.1.5.3.2.5 presents estimated results for Poisson's ratio (range of 0.11 to 0.43), as well as load and deflection properties (BSC 2002a, Sections 6.2.5 and 6.2.6). SAR Section 1.1.5.3.2.5 attributes the wide range in Poisson's ratio to heterogeneities in lithostratigraphic units. Plate load tests were completed on the alluvium in or near the surface facilities area for the muck conveyor, and at the Booster Pump Station (Riggins 1994a; Riggins 1994b; Riggins 1995).

Dynamic Shear Modulus and Damping Ratio—Dynamic shear moduli and damping ratios as functions of shear strain for the surficial alluvium (soil) and the underlying tuff (rock) are used for dynamic site response analyses for surface facilities. Estimates of these properties are based on evaluating the results of combined resonant column and laboratory torsional shear testing of the dynamic properties of tuff and alluvium samples obtained from boreholes UE-25 RF#13 through

UE-25 RF#17 (Figure 5-6). Test results are available for strain-dependent dynamic shear moduli and damping ratios. SAR Section 1.1.5.3.2.6 provides additional discussion of these data.

5.2.4.2.2 Rock Material Properties for Subsurface Facilities

This section summarizes the geotechnical properties of the rocks within which the underground excavation of the geologic repository will take place. Numerical values of geotechnical properties are discussed and presented in SAR Section 1.1.5.3, and application of these data to postclosure drift stability and degradation is presented in SAR Section 2.3.4.

Seismic Velocity Profile—Shear-wave seismic velocity profiles have been sampled by spectral analysis of surface waves, downhole seismic, and vertical seismic profiling surveys. Compression-wave seismic velocity profiles at the repository have been sampled by vertical seismic profiling surveys. Spectral analysis of surface-wave surveys were performed both from the ground surface near the crest of Yucca Mountain and in the ESF. Shear-wave velocities in the tunnel range from 6,000 to 7,000 ft/s for intact rock with few fractures. When the rock is fractured, these values decrease to the general range of 3,000 to 4,000 ft/s (BSC 2004j, Section 6.2.3.2.4).

Density and Porosity—Rock density and porosity influence strength and deformation characteristics, dynamic properties, and thermal properties. Rock density and porosity represent volumetric averages that depend on the scale of measurement, which varies from relatively small to large laboratory specimens of intact rock to much larger volumes of intact rock mass. The extent of lithophysae in a rock volume has a direct effect on density and porosity. Dry density for nonwelded tuff is about 1.28 g/cm^3, while the welded tuff ranges from 2.12 to 2.35 g/cm^3 (BSC 2004a, Section 3.7.3.1.1). Mean density in the lithophysal units is lower, ranging from 1.83 to 2.21 g/cm^3 (BSC 2007a, Table 6-6). A density of 2.2 g/cm^3 was adopted for the tuff for purposes of the site response analysis (BSC 2004j). Mean matrix porosity for the Topopah Spring Tuff nonlithophysal units generally varies from 10% to 12%. In lithophysal units, the mean matrix porosity ranges from 15% to 17% with lithophysal porosity ranges from 9% to 13% (BSC 2007a, Table 6-6).

Static Rock Strength—The static strength of host rock is fundamental to rock stability, including tunnel rockfall analyses. Static rock strength is characterized in terms of the strength of intact rock, the strength characteristics of natural rock fractures, and the composite strength characteristics of the rock mass, which include the effects of fractures (BSC 2007a, Sections 6.4.2 and 6.4.3). For intact rock, the strength was determined by performing unconfined compression, triaxial compression, and Brazilian tensile tests in the laboratory on intact samples of rock. Most of the tests were of the unconfined type because this type of test is simple to perform, and the results are often used as an index parameter. Strength values for rock fractures are estimated on the basis of cohesion, friction angle, and elastic normal and shear stiffness. Strength values may be determined at peak, ultimate, or residual strength values. Peak strength refers to the maximum shear stress. Ultimate strength refers to the steady-state shear stress reached with continued shearing. Residual strength refers to the lower-bound shear strength after damage from shearing has removed all asperities from fracture faces (BSC 2007a, Sections 6.4.2 and 6.4.3.1).

Strength characteristics of the rock mass, including effective friction angle and effective cohesion, are estimated using the generalized Hoek-Brown criterion (Hoek et al. 2002). Parameter inputs to the criterion are based on compression and tensile strengths from laboratory testing of intact rock specimens and tunnel conditions determined through geologic mapping (BSC 2007a, Section 6.4.4.2.2).

Static Deformation Properties—Static deformation properties, including Young's modulus, shear modulus, and Poisson's ratio, are used to estimate potential rock strains (deformations) in the underground facility. These properties are estimated from results of geophysical surveys, laboratory testing of rock specimens, in situ borehole jack tests, plate load tests, slot tests, and analytical modeling. Testing results and estimated properties for small strains (less than 0.001% strain, based on dynamic testing) and for large strains (based on quasi-static tests) are used (BSC 2007a, Section 6.4.2.2.1, Tables 6-15 and 6-17).

Dynamic Shear Modulus and Damping Ratio—Dynamic shear moduli and damping ratios provide necessary input to site response analyses. Resonant column and torsional shear tests were performed on 10 intact core samples from three surface-based boreholes (USW SD-9, UE-25 SD-12, and USW NRG-7/7a) located along the ESF main drift (Figure 5-6). Four of the specimens were classified as welded tuff, while six specimens were classified as nonwelded tuff (Stokoe et al. 1998, pp. 1 and 2, and Table 1). Test results and estimated properties are discussed and summarized in SAR Section 1.1.5.3.

Thermal Properties—Thermal properties include thermal conductivity, heat capacity (specific heat) and thermal capacitance, and coefficient of thermal expansion. Rock thermal properties have been estimated from numerous laboratory tests and field tests conducted on various lithostratigraphic units of the tuffs. Rock thermal properties are variable depending on the percentage of void space in lithophysal rocks and the fracture characteristics and frequency in nonlithophysal rocks. Intact rock thermal conductivity measurements for the lithophysal tuff range from 1.73 to 2.18 W/m·K (BSC 2007a, Section 6.5.3.1.1, Table 1). Thermal property data and estimated thermal properties are used for predicting thermal responses in the host rock because of waste emplacement (BSC 2007a, Section 6.5).

In Situ Stress Conditions—Estimates of the magnitude, direction, and variability of the preconstruction in situ state of stress are used in the analysis and design of stable underground openings, as well as for the prediction of short-term and long-term rock-mass deformation (BSC 2007a, Section 6.4.4.4.1.2). Hydraulic fracturing tests performed for ambient characterization of the Drift Scale Test block measured in situ stresses in the rocks of the Tptpmn. These data are used to define initial and boundary conditions for drift stability models used in repository performance assessment (SNL 1996; CRWMS M&O 1997c, Section 10.4).

5.2.4.3 Geotechnical Features and Processes Used to Estimate Postclosure Performance

Parameters reflecting geotechnical properties and conditions are important for model development and analysis supporting the TSPA. SAR Section 2.2 tabulates the complete set of FEPs that are included in the process and abstraction models supporting the TSPA. Analyses of rockfall impacts on EBS features, described in SAR Section 2.3.4, consider three sources:

- In situ and thermal stress loading
- Seismic loading
- Drift degradation due to time-related strength loss of the rock mass.

Mechanical properties of intact rock matrix and fractures, thermal properties, and large-scale properties of the lithophysal rock mass are important for these analyses. The mechanical effects of excavation on near-field rock properties are also included in models supporting the TSPA. SAR Sections 1.1.5 and 1.3.2 provide information about rock parameters as they pertain to subsurface design and drift stability.

5.2.4.4 Geotechnical Data from Exploratory Excavations

A series of site-specific field tests were conducted in the ESF and the ECRB Cross-Drift. Access to the host rock and surrounding units allowed geologic mapping of fracture geometry and characterization of the amount of lithophysal porosity, which are the primary geologic structural features affecting rock mass behavior. Laboratory test results on elastic and strength properties for intact rock show that porosity is a major factor controlling variability in mechanical properties (BSC 2007a, Section 6.4).

Although important, field tests are not the only sources of information about rock performance. Other field activities providing information about the rock involve mapping of the exposed excavation walls, in situ deformation measurements, steel set load measurements, and observations of the performance of rock and ground support elements that are applied to maintain safety and stability of existing excavations. Data originating from all available sources are analyzed because each approach offers a unique methodology of evaluating and quantifying the performance of lithostratigraphic rock units and the engineering components used in ground control.

The types of tests and other field activities performed to enhance an understanding of rock mass behavior and in situ performance of ground control hardware installed to maintain the safety and stability of underground excavations included the following (BSC 2007a, Section 6.6.1):

- Single Heater Test

- Drift Scale Test

- Rock Mass Mechanical Field Tests:

  - Borehole Jack Tests
  - Plate Loading Test
  - In Situ Slot Tests

- ESF Ground Support Confirmation

- ESF Deformation Monitoring
- Steel Sets Monitoring.

Studies in western Midway Valley for design of the repository surface facilities have provided the data used to develop site-specific seismic design response spectra and time history for defining seismic design input ground motions. Material properties necessary for modeling soil–structure interactions have been developed, including shear modulus and dynamic damping ratio as a function of shear stress. In conjunction with lithostratigraphic and structural data collected from surface-based boreholes, surface wave surveys have been used to determine thickness of alluvial materials and locations and directions of movement on faults and fault splays (BSC 2002a, Section 6.6.2).

5.2.5 Overview of the Meteorology and Climatology of the Yucca Mountain Site

Meteorological information has been collected at and near Yucca Mountain for purposes of characterizing the environment with regard to average and extreme weather conditions and providing a basis for estimating atmospheric dispersion of potential airborne releases. Present-day climate and evidence of past climates in the region have been studied to provide a basis for estimating the range of future climate variability. Temperature and the timing, frequency, and duration of precipitation can affect infiltration and rates of water movement through the unsaturated zone repository environment. Future wetter or cooler climates would afford increased opportunities for infiltration with consequent increased amounts of unsaturated zone flux.

This section provides a summary of current climatic and meteorological conditions in the Yucca Mountain region. The nature, timing, and magnitude of past climate changes are summarized, and the approach used for forecasting future climatic conditions on the basis of paleoclimate data, combined with data from present-day analogue meteorological monitoring sites, is described. Finally, this section summarizes forecasted long-term, future climatic scenarios and conditions at Yucca Mountain, based on analysis of these combined data sets. SAR Section 2.3.1 provides additional information about climate analysis and infiltration models developed for the TSPA.

SAR Section 1.1.3 provides meteorological and climatological information used to support preclosure safety evaluations.

5.2.5.1 Present Climate and Controlling Influences

Climate in Yucca Mountain region is dependent upon its location relative to local topography and is controlled by changes in atmospheric circulation patterns. SAR Section 2.3.1.2.1.2.1 provides further discussion of the influence of global circulation patterns on the climate in the Yucca Mountain region. The present-day climate is relatively arid, with annual precipitation totals ranging between approximately 100 and 300 mm/yr (DOE 2002b, Section 3.1.2.2; SNL 2006, Section 7.1), and is generally characterized by hot summers and typically dry and cool winters.

As described in SAR Section 2.3.1.2.1.2.1 and *Future Climate Analysis* (BSC 2004g, Section 6.2), seasonal expansion and contraction of tropical and polar air masses, and the position of the mixing zone between them (called the westerlies) provide the framework for regional climates in the United

States. The general climate associated with these air masses is often modified by regional features, such as topography, large lakes, and the oceans. Precipitation in the Yucca Mountain region is heavily influenced by these atmospheric features, combined with the location of Yucca Mountain, which is east of the Sierra Nevada and Transverse ranges. Potential sources of moisture for the Yucca Mountain region are the Pacific Ocean and the Gulf of Mexico (BSC 2004a, Sections 6.3.1 and 6.3.2). The Sierra Nevada and Transverse ranges west of Yucca Mountain form a significant impediment to the movement of Pacific air, especially during winter, resulting in a rain-shadow effect. A rain shadow is an area of dry land that lies on the leeward (or downwind) side of a mountain. The heaviest rainfalls at Yucca Mountain normally occur during late July. Less commonly, in September and sometimes October, remnant moisture exported northeastward from dying tropical storms off the Baja California coast can produce heavy precipitation (BSC 2004a, Section 6.3.1).

Additional information about the characteristics of the regional climate is provided in SAR Section 2.3.1.

5.2.5.2 Description of Local and Regional Meteorological Program Results

Data regarding precipitation, temperatures, wind speeds, and other meteorological parameters in the Yucca Mountain region have been obtained from a series of local meteorological and weather monitoring stations established by the DOE at or near Yucca Mountain (Figure 5-20), and from more than 15 National Weather Service regional meteorological monitoring stations in central and southern Nevada. The National Weather Service stations are located at distances between approximately 15 km and 464 km from Yucca Mountain, and they provide a longer record of temperature and other weather data than the local meteorological monitoring sites (SAR Figure 1.1-13). The locations and distribution of the DOE meteorological monitoring sites were determined, in part, based on guidance contained in ANSI/ANS-3.11-2005, *American National Standard for Determining Meteorological Information at Nuclear Facilities*, Regulatory Guide 1.23, and guidance issued by the U.S. Environmental Protection Agency (EPA 2000). These sites were selected to provide representative data regarding meteorological conditions in topographically diverse settings for the purpose of making atmospheric dispersion estimates for potential airborne releases.

Data collected from stations Sites 1, 2, 3, 6, and 9, operated by the DOE, and from Amargosa Farms–Garey, Cane Spring, Area 12, Site 4JA, 40MN, MEDA 12, and MEDA 26, operated by the National Oceanic and Atmospheric Administration and National Oceanic and Atmospheric Administration/Air Resources Laboratory/Special Operations Resource Division, were used to evaluate present-day and future climate conditions for use in the infiltration model (SNL 2006, Section 7).

Meteorological conditions measured at Site 1 (Figure 5-20) are representative of conditions at the location of the repository surface facilities. Site 2, on top of Yucca Mountain near its northern end at an elevation of about 1,478 m above mean sea level, is used to characterize precipitation, temperature, airflow, and other meteorological conditions along this portion of the Yucca Mountain ridge crest. The crest of Yucca Mountain, at the location of the repository, is approximately 1,400 to 1,500 m above mean sea level (SAR Section 1.1.1.2). Site 9, the southernmost meteorological monitoring site, is located in northern Amargosa Valley and provides data used for biosphere modeling.

5.2.5.2.1 Local and Regional Precipitation Characteristics

Locally, as well as regionally, precipitation rates vary on a seasonal basis and are affected by local topographic features. Extreme precipitation events generally occur within the Yucca Mountain region in a sporadic and episodic fashion, and are typically of short duration. In this part of the United States, the wettest day typically brings about a quarter to a third of the annual mean precipitation. At a frequency of once every 50 to 100 years, the wettest annual day rivals the mean annual total precipitation in the driest locations (BSC 2004a, Section 6.3.3.2.2).

Annual total precipitation varies significantly from year to year, and to a lesser extent according to the elevation and location relative to terrain features. The annual precipitation average at Site 1 was 200.8 mm. Precipitation at Site 1 was infrequent, so short-term large amounts affected long-term totals (BSC 2007c, Section 5.3).

From the analysis of local meteorology for the period of 1994 to 2006 (BSC 2007c), the range of average annual totals differed by nearly a factor of two across the sites, with 116.0 mm at Site 9 and 225.3 mm at Site 6. The average annual totals at Sites 1, 2, 4, 7, 8, and 401 were within a few millimeters of 200 mm. The summaries show the average annual total precipitation varied considerably from year to year. For example, the Site 1 annual totals for the period from 1994 through 2006 ranged from 39.6 mm in 2002 to 366.5 mm in 1998, a factor of more than nine (BSC 2007c, Section 5.1.1).

5.2.5.2.2 Local Temperature Ranges and Extremes

Mean daytime and nighttime air temperatures in the vicinity of Yucca Mountain typically range from 34°C to 22°C in the summer and from 10.5°C to 2°C in the winter (DOE 2002b, Section 3.1.2.2). The winter season is mild, with some periods of below-freezing temperatures. Temperature extremes range from −15°C in winter to 45°C in summer at a National Weather Service station near Mercury on the Nevada Test Site, which is located approximately 40 km southeast of Yucca Mountain (BSC 2004a, Table 6-17. Note: this table is based on an 11-year period from 1986 to 1996). The modest elevation (1,000 to 1,500 m) at Yucca Mountain is enough to prevent occurrence of the extremely hot temperatures reached in southwestern deserts at lower elevations. In the dry and cloudless air, surfaces cool efficiently, and daily temperature ranges can be large.

At Site 1, the annual mean maximum and extreme maximum temperatures were 23.6°C and 43.3°C, respectively. The annual cycle of monthly mean maximum temperatures varied seasonally from 12.2°C to 37.0°C. The annual mean minimum and extreme minimum temperatures were 9.3°C and −10.9°C, respectively. The annual cycle of monthly mean minimum values seasonally ranged from +0.4°C to 20.5°C. These mean maximum and minimum monthly averages showed a large diurnal change, ranging from about 12°C in winter to nearly 17°C in summer. The overall annual mean temperature at Site 1 was 16.6°C. On average at Site 1, there were 99 days each year with maximum temperatures reaching 32.2°C or higher; virtually all of July and August met this criterion. Also at Site 1, there was an average of 44 days each year when the minimum temperature dropped to 0°C or less.

In contrast to the valley location of Site 1, the ridge-top location of Site 2 had a lower annual mean temperature of 15.8°C (BSC 2007c and Table 5-2). The annual mean maximum and extreme maximum temperatures were 21.4°C and 42.7°C, respectively. The annual cycle of monthly mean maximum values ranged seasonally from 9.7°C to 35.3°C. The annual mean minimum and extreme minimum values were 11.3°C and −10.4°C, respectively. Thus, the average diurnal range in temperature was 7°C in winter and 13°C in summer. The daily temperature range at Site 2 was less than at Site 1, due to the differences in terrain exposures at the sites. Site 2 averaged 78 days each year when maximum temperatures reached 32.2°C or higher, and 31 days when the minimum temperature dropped to 0°C or less (BSC 2007c, Section 5.1.3).

5.2.5.2.3 Humidity and Evaporation

The atmosphere in southern Nevada is characterized by very low relative and absolute humidity. Winter months tend to have higher average relative humidity levels, while summer values are lower. Relative humidity levels range from about 10% on summer afternoons to about 50% on winter mornings, and to nearly 100% during precipitation events (DOE 2002b, Section 3.1.2.2). Daily relative humidity extremes tend to occur near 0400 and 1600 PST because these times are near the minimum and maximum air temperature occurrences. The mean monthly and annual relative humidity show the overall dry conditions that occur in this arid region.

At Site 1, the annual average relative humidity ranged from 21.1% at 1600 PST to 40.5% at 0400 PST; the average afternoon (1600 PST) value during June was 9.5% (BSC 2007c, Section 5.1.4)

Evaporation and transpiration (also called evapotranspiration) are two factors that help determine soil moisture content, and, hence groundwater recharge. See SAR Section 2.3.1.3.1.2 for a description of the role played by evapotranspiration in infiltration into the repository. The rates of water loss are strong functions of wind, atmospheric humidity, temperature, and, to a lesser extent, solar radiation. For the present-day climate at Yucca Mountain, the average potential annual evapotranspiration rate is approximately nine times greater than the average annual precipitation rate, as described in SAR Section 2.3.1.3.3.1.2. Although there are few direct local measurements of actual or potential evaporation, a National Weather Service station at Boulder City, Nevada (about 26 mi south-southeast of Las Vegas), shows a long-term (1931 to 2000) average potential evaporation rate of 2,947 mm/yr (BSC 2004a, Section 6.3.3.2.6).

5.2.5.2.4 Lightning Characteristics and Frequency

Lightning can accompany severe weather conditions that occasionally occur in the region, typically in the form of summer thunderstorms. Data on cloud-to-ground strikes from 1991 to 1996 are available from an automated lightning detection system installed on the Nevada Test Site as part of the Air Resources Laboratory and the Special Operations and Research Division of the National Oceanic and Atmospheric Administration. Data characteristics documented for each lightning strike include latitude, longitude, date and time of occurrence, and positive or negative signal sign (CRWMS M&O 1997d, Sections 2.6 and 4.2.2.4). For a 3,600 km^2 area around Yucca Mountain, lightning strikes occurred most frequently during August, with a secondary strike maxima occurring in May. The lightning-strike ratio in the repository operations area is approximately 0.41 strikes per square kilometer per year or less for all strikes. This strike-density range is slightly lower than the results from a survey showing from 0.5 to 3 strikes per square kilometer in a large zone, including Arizona, southern Nevada, and northward through the Rocky Mountains (CRWMS M&O 1997d, Section 4.2.2.4).

5.2.5.2.5 Local Wind Characteristics, Including Tornadoes

Wind patterns in the Yucca Mountain area are a result of local topography and synoptic- and regional-scale weather patterns. The primary influence on local wind is topography, with air flow toward higher terrain in the daytime and away from higher terrain at night (DOE 2002b, Section 3.1.2.2). Local wind patterns also have a strong diurnal cycle of daytime winds from the south and nighttime winds from the north. Synoptic- and regional-scale weather systems can significantly alter the typical diurnal cycles. In the desert environment, the surface and upper flows are much more strongly coupled during daytime and often completely decoupled at night. The strongest winds in southern Nevada are likely to be from the southern and western quadrants, and associated with thunderstorms (BSC 2004a, Section 6.3.3.2.4). The following sections describe wind direction and speeds and extreme wind conditions in the Yucca Mountain region.

Wind Directions and Wind Speeds—It is important to understand prevailing wind directions and velocity in order to estimate the transport of ash from a volcanic event, and for estimating the redistribution of the ash after it has reached the ground. Historical data on recorded wind speeds and wind directions in the Yucca Mountain region are available from many of the same meteorological monitoring sites and National Weather Service weather stations that are sources for temperature data. Wind-direction and wind-speed data collection efforts have historically concentrated on Sites 1 to 9 to characterize local airflow and support evaluation of atmospheric dispersion (BSC 2004a, Section 6.3.3.2.4). Wind parameters measured at these sites include wind direction and horizontal and vertical wind speed at a height of 10 m above ground level at Sites 1, 2, 4, and 9, and at a height of 60 m above the ground at Site 1. The initial focus of the network was to monitor airflow toward Amargosa Valley from Midway Valley (the site of the repository surface facilities). As described earlier, Site 9 is located near the southern boundary of the Nevada Test Site, near Amargosa Valley, and provides data used for biosphere modeling.

Wind speed varied by diurnal and seasonal cycles. Daytime speeds were generally higher than nighttime, though the persistent nocturnal down-slope winds at the valley floor sites kept the nighttime averages higher than would occur otherwise. The highest monthly average speeds occurred in April. The extreme three-second gust speed at Site 1 was 27.6 m/sec (about 62 mph), while the hilltop location of Site 4 on Alice Hill experienced a gust of 39.9 m/sec (almost 90 mph). With one exception, the maximum one-minute average wind speeds occurred from a northwesterly direction.

Joint frequency distributions of wind speed and wind direction by time of day and stability categories showed regular cycles influenced by local terrain. Unless large scale weather systems overrode the local-scale wind dynamics related to terrain, daytime unstable conditions occurred with winds from southerly directions. Terrain features tended to channel airflow in directions along the axis of valleys during the daytime periods. Surface cooling in the clear-sky environment led to stable periods with cold air flowing down local slopes and large valley areas at night, particularly in the valley floor locations. The down slope directions were generally from the west to north on the eastern flank of Yucca Mountain and in Jackass Flats (BSC 2007c, Section 5.3).

The maximum observed 3 second wind gust (basic wind speed) was measured at 10 m above the ground at Site 1 for the period. The peak three-second gust was 27.6 m/sec, and the fastest one-minute average speed was 23.3 m/sec at Site 1. The data from Sites 2 and 4 show the influence of terrain on maximum wind speeds. The peak three-second gust was 38.7 m/sec, and the fastest one-minute average speed was 33.1 m/sec on the ridge top location of Site 2. The hilltop location of Site 4 on Alice Hill in the northeast portion of Midway Valley experienced yet higher speeds. The peak three-second gust at Site 4 was 39.9 m/sec, and the fastest one-minute average speed was 35.8 m/sec. The valley floor location of Site 9 experienced unusually high maximum speeds during July, with the peak three second gust of 33.1 m/sec and the fastest one-minute average speed of 27.5 m/sec (BSC 2007c, Section 5.1.2).

The mean monthly speeds at the 10 m level at Site 1 ranged from 3.0 m/sec in January to 4.2 m/sec in April, and the annual average was 3.5 m/sec. On the ridge top location of Site 2, the mean monthly speeds ranged from 3.9 m/sec in the winter months to 5.4 m/sec in April, and the annual average was 4.4 m/sec. The consistent occurrence of drainage winds at night at Site 9 kept the mean speed higher than it might otherwise experience. The mean monthly speeds at Site 9 ranged from 4.0 m/sec in the winter months to 4.9 m/sec in April, and the annual average was 4.4 m/sec (BSC 2007c, Section 5.1.2).

Tornadoes—Tornadoes are infrequent and weak in the Yucca Mountain region, primarily because the generally dry weather conditions and the rough, irregular terrain are unfavorable for tornado generation. Data are available on reported tornado occurrences within the Great Basin region, encompassing most of Nevada and portions of Utah, Arizona, and California (Figure 5-28) for the period between January 1, 1950, and September 30, 2003 (Deng 2004a, Deng 2004b, Deng 2004c, Deng 2004d). There were no tornadoes of category F2 (wind speeds of 113 to 157 mph) or higher reported in Nevada during this period. Three category F0 tornadoes (winds less than 72 mph) occurred in the vicinity of Yucca Mountain (Deng 2004a). SAR Section 1.1.3.6 discusses severe weather characteristics considered in developing the design basis value for wind speeds.

5.2.5.2.6 Atmospheric Stability

Atmospheric stability is an indicator of the potential strength of the horizontal and vertical atmospheric mixing processes. Heating of the ground surface during the largely cloudless daytime periods contributes to instability because air near the ground warms, becomes less dense, rises, and, thus, effectively enhances mixing conditions. The opposite occurs when clear sky during nighttime hours allows the ground surface to cool, causing increasing temperatures with height and suppressing vertical mixing. The Yucca Mountain area typically exhibits unstable to moderate atmospheric stability conditions during daytime hours, and stable conditions during the nighttime hours (BSC 2004a, Section 6.3.3.2.7).

Stability data provide information relevant to modeling dispersion of airborne material. Information on wind characteristics is also directly relevant to characterizing atmospheric dispersion, because airflow controls transport pathways and dilution. Wind patterns are influenced by topographic channeling and are overprinted by regional airflow and by diurnal and seasonal cycles at Yucca Mountain (BSC 2004a, Section 6.3.3.2.7).

Data from DOE Sites 1 through 9 indicate that atmospheric stability ranges from very stable to extremely unstable (CRWMS M&O 1997e, Section 3.2). Site-specific data obtained at Site 1 can be used to categorize atmospheric stability for modeling applications, as recommended in Regulatory Guide 1.23. This approach uses temperature differences measured from the 10 m level to the 60 m level to determine stability categories. These categories range from extremely unstable through extremely stable. Wind-speed and wind-direction data obtained from Site 1, together with this stability classification information, are also used as inputs for downstream atmospheric dispersion modeling.

At Site 1, the unstable categories occurred during 28.5% of the total hours, mostly during daytime hours. The stable categories occurred during 56.7% of the total hours, mostly during nighttime hours and during some transition periods. The neutral category occurred during 14.9% of the total hours, mostly during the day portion of the transition between daytime and nighttime (BSC 2007c, Section 5.2.1).

Additional information on atmospheric dispersion is available in *Engineering Design Climatology and Regional Meteorological Conditions Report* (CRWMS M&O 1997d) and *Local Meteorology of Yucca Mountain, Nevada, 1994–2006* (BSC 2007c, Section 5.2).

5.2.5.3 Paleoclimatology

Projections of future climate change are based on an evaluation of paleoclimate data that span 800,000 years (BSC 2004a, Sections 6.4.1 and 6.5). Determining the appropriate length of the geologic record to examine as the basis for predicting future climate at Yucca Mountain depends on an understanding of the forcing mechanisms for climate change, as described in SAR Section 2.3.1.2.1.2.3. Precession of the earth's axis in space and the eccentricity of the earth's orbit influence the climate because they impact the total radiation received in the upper atmosphere. Precession operates on a cyclic timescale of 19,000 to 23,000 years, while eccentricity cycles operate on approximately 100,000 year timescales with four 100,000 year cycles forming a longer 400,000 year eccentricity cycle (Sharpe 2003, Section 6.4.2). The influence of these earth-orbital cycles on global climate is well established through scientific observations and theory (BSC 2004g, Section 5).

Together with earth-orbital information spanning 800,000 years, evidence of climate change for the past 568,000 years is interpreted from calcite vein deposits in Devils Hole, which is a water-filled fracture zone located approximately 60 km southeast of Yucca Mountain (BSC 2004a, Section 6.4.1.1). In addition, core samples from lake deposits in Owens Lake, a playa 160 km west of Yucca Mountain, contain paleoclimatic indicators (pollen, plant remains, microfossils) that have been used to establish a climate progression in the region (BSC 2004a, Section 6.4.1.2).

The remainder of this section, and Section 5.2.5.4, provide an overview of the approach used to forecast climate states for the next 10,000 years for use in the TSPA.

5.2.5.3.1 Sequence and Nature of Past Climates

DOE investigations have included analysis of regional and local paleoclimate indicators. These indicators include the following (BSC 2004a, Section 6.4):

- Climate change chronology from calcite precipitation on fracture walls at Devils Hole, California

- Microfossil and sedimentary evidence of past changes in temperature and precipitation in cores from Owens Lake, California, and past discharge sites near Yucca Mountain

- Paleovegetation records from preserved pack-rat middens.

Figure 5-21 shows the localities of features that provide information on past climatic conditions that have been used for estimating future climates in the Yucca Mountain region. Detailed studies of paleoclimatic indicators provide information on temperature and precipitation patterns, and on durations and sequencing of past climate states upon which to base extrapolations of future climatic conditions in the Yucca Mountain region. Analysis of the paleoclimate records indicates that climate sequences occur in cycles regionally and worldwide, moving from interglacial to glacial climate states and back again (BSC 2004a, Section 6.5.2.1).

Using geographic and climatic distributions of extant representatives of the microfossils found in the Owens Lake sedimentary record, various investigators have identified evidence of the following climate states as distinct climate types (BSC 2004a, Section 6.5.2):

- Interglacial
- Intermediate/monsoon
- Glacial transition
- Glacial.

The interglacial state is the present-day climate, whereas the intermediate/monsoon state is characterized by hotter summers with increased summer rainfall relative to today. The glacial-transition climate is the intermediate state, and is characterized by cooler and wetter climatic conditions than today. Finally, the glacial climate state is characterized by lower mean annual temperatures, higher mean annual precipitation, and, therefore, much greater effective moisture (which is precipitation minus evaporation) relative to today. Both the glacial-transition and the glacial climate states will have much greater effective moisture conditions than today, and lead to higher infiltration rates (BSC 2004a, Section 6.5). The glacial-transition state will be the most prevalent future climate state, and interglacial and glacial states will be of shorter durations. Monsoon climate states are the shortest duration, lasting a few hundred to a few thousand years, nested within the glacial-transition state (BSC 2004a, Section 6.5.2).

5.2.5.3.1.1 Evidence for Chronology of Climatic Sequences: Devils Hole

The walls of Devils Hole—a water-filled, cave-like, extensional fracture zone in the regional carbonate aquifer, located about 60 km southeast of Yucca Mountain (Figure 5-21)—are lined with a thick layer of dense vein calcite. These calcite vein deposits provide a record of isotopic variation in the regional aquifer for the last 568,000 years. The oxygen isotope record from the Devils Hole calcite deposits provides a chronology for past glacial and interglacial periods in the Yucca Mountain region (BSC 2004a, Section 6.4.1.1).

The calcite deposits at Devils Hole precipitated slowly and continuously from groundwater, and record variations in oxygen isotope values ($\delta^{18}O$) that are indicators for past climate regimes, based on oxygen isotope stages recognized in the marine carbonate stratigraphic record (Winograd et al. 1992, p. 255). Changes in the $\delta^{18}O$ values in marine carbonates reflect changes in ocean water through time as continental ice sheets advanced or retreated. SAR Section 2.3.1.2.1.2.3 provides further discussion of the time-series plots of $\delta^{18}O$ values derived from Devils Hole cores that are used to infer relative climate conditions, which are trends toward either glacial or interglacial climate states. The next step in forecasting future climates is to correlate the climate cycles observed in Devils Hole to orbital patterns of the earth in space: precession and eccentricity (BSC 2004g, Section 6.4).

Precession, the slow migration of the earth's rotational axis in space, changes the seasonal and latitudinal distribution of solar radiation at the top of the earth's atmosphere and varies on a cyclic timescale of 19,000 and 23,000 years (Sharpe 2003, Section 6.4.2). Eccentricity, which is the variation in shape of the earth's orbit from elliptical to circular, affects the annual total radiation received in the upper atmosphere, also influencing climate. Eccentricity cycles operate on approximately 100,000 year timescales, and four of these 100,000 year cycles form a longer 400,000 year eccentricity cycle. At present, the earth resides at approximately the end of the 400,000 year eccentricity cycle, and is poised to begin a new 400,000 year cycle (Sharpe 2003, Section 6.4.2). SAR Section 2.3.1.2.1.2.3 provides further discussion of earth-orbital parameters and timing of climate change.

The Devils Hole record, which is dated by the U-series method, is generally regarded as containing the most accurately dated climate change record in the region and is, therefore, used to compare to precession and eccentricity cycles over the last 400,000 years (BSC 2004a, Section 6.5.3). This comparison provides the basis for forecasting climate. Although the Devils Hole oxygen isotope record can be used to identify climate states, the characteristics of past climate states cannot be interpreted from this record (BSC 2004a, Sections 6.5.3.4, 6.4.1.1, and 6.5.3.5). The Owens Lake and other long-term climate records provide additional information that is used for reconstructing the nature of past climatic conditions during the last long earth-orbital cycle (last 400,000 years) (BSC 2004a, Section 6.4.1.2).

5.2.5.3.1.2 Additional Evidence for Climatic Sequences and Evidence for Past Climates: Owens Lake Basin

Owens Lake, a playa on the eastern side of the Sierra Nevada Range in Inyo County, California, about 160 km west of Yucca Mountain, contains a thick sequence of lake deposits. Core samples obtained from these deposits contain paleohydrologic and paleoclimatic features that allow reconstruction of regional glacial and interglacial climates over the last 800,000 years (Forester et al. 1999; BSC 2004a, Section 6.4.1.2). Because climate phenomena operate on regional scales, past climates experienced at Owens Lake are likely to resemble climates at Yucca Mountain. The Owens Lake sediments contain fossil pollen, plant remains, diatoms, ostracods, and sedimentological and geochemical data (BSC 2004a, Sections 6.4.1.2.2, 6.5.3.4, 6.5.3.5, and 6.5.4).

Changes in ostracod and diatom assemblages in Owens Lake cores can be translated into a climate progression from periods when the area was dominated by fresh waters, indicative of cooler, wetter climates, to periods dominated by sodium-bicarbonate-rich waters, indicating dry climates and a greater contribution of spring discharge into Owens Lake (BSC 2004a, Section 6.5.2). It was concluded that climate and hydrologic environments similar to today (interglacial) occurred for about 20% of the last 400,000 years; whereas wetter climates (monsoon, glacial-transition, and glacial) than today with dilute, fresh waters persisted for about 80% of the time (BSC 2004a, Table 6-33). Past climatic states interpreted from the Owens Lake record are generally consistent with the changes observed in Devils Hole. The records show the same sequence of glacial and interglacial events, although the timing estimates are not always consistent. SAR Section 2.3.1.3.3.1.2 describes the application of these data for climate analysis and infiltration modeling.

Study of pack-rat middens provided an additional line of evidence about past climates that can be used to supplement the understanding of the timing of future climates and sequences of climate change. Preserved pack-rat middens contain the macrofossil remains of plant assemblages that were gathered by pack rats from the immediate vicinity of the middens. Plant assemblages recovered from middens were used to evaluate precipitation and temperature characteristics of past climates (Thompson, R.S. et al. 1999, pp. 2 and 34; BSC 2004a, Section 6.4.2.1).

Analysis of pack-rat midden data, when compared to present-day mean annual temperature and mean annual precipitation values in the vicinity of Yucca Mountain, indicates the following (BSC 2004a, Section 6.4.2.1; Thompson, R.S. et al. 1999, p. 34):

- Between about 35,000 to 30,000 years ago, mean annual temperature was about 4°C colder than present-day mean annual temperature, and mean annual precipitation was about 1.5 times the present value.

- Between about 27,000 and 23,000 years ago, mean annual temperature was about 5°C colder than present mean annual temperature, and mean annual precipitation was about 2.2 times the present value.

- Between about 20,500 and 18,000 years ago, the last glacial maximum, mean annual temperature was about 8°C colder than present, and mean annual precipitation was about 2.4 times the present value.

- Between about 14,000 and 11,500 years ago, mean annual temperature was about 5.5°C colder than present, and mean annual precipitation was about 2.6 times the present value. Thompson, R.S. et al. (1999) specify that these values are “For 5000 ft (1524 m) at the Yucca Mountain repository....” This elevation is greater than the crest at any point over the repository.

5.2.5.4 Forecast Timing and Sequence of Future Climates for Use in the TSPA

Cyclic climate sequences and inferred climate conditions occurring during the past two successive 400,000 year long earth-orbital cycles were used to estimate future climate states, as follows (Sharpe 2003, Sections 5 and 6.1):

- The sequencing and duration of past climate states (glacial, interglacial, monsoon, and glacial-transition) suggested by the Owens Lake, California, paleoenvironmental record were used.
- The Devils Hole reconstructed climate intervals from approximately 560,000 to 60,000 years ago were correlated to orbital parameters, based on astronomical forcing mechanisms to identify a pattern of past climate change.
- Present-day meteorological analogue stations were identified to represent these past climate states. The record of daily temperature and precipitation from these stations was used to represent future temperature and precipitation.
- The inferred pattern of climate change was projected to predict the nature and timing of future climate change.

Recently, new results (Winograd et al. 2006, p. 255) were presented that extended the record at Devils Hole from 567,700 to 4,500 years ago. The new record overlapped the previous record (to 60,000 years) and closely resembles sea surface temperature time series from sediments cored off the California coast, further enhancing the Devils Hole as a source for future climate predictions. To establish the starting point for forecasting climate change for the next 10,000 years, a point equivalent to the present day was identified in the past climate sequences. Evidence from the Owens Lake sedimentary record and Devils Hole chronology supports selection of an analogue time of about 400,000 years ago as being equivalent to the present-day climate. This information was then used in conjunction with orbital precession information to forecast the sequence and duration of future climate states in the Yucca Mountain region during the next 10,000 years (BSC 2004g, Section 6.6).

Three climate states are forecast to occur within the next 10,000 years (BSC 2004g, Section 6.6):

- A continuation of a present-day climate for about the next 400 to 600 years
- An interglacial monsoon climate of warm but wetter conditions than present for about the following 900 to 1,400 years
- A cooler, wetter, glacial-transition climate that would persist through the remainder of the 10,000 year period.

The first period of full glacial conditions was forecast to occur at about 30,000 years after the present (BSC 2004a, Section 6.5.5.3). SAR Section 2.3.1.2.1.2 provides further discussion of the approach used to forecast climate change.

A series of present-day analogue sites located in various western states was chosen as a surrogate for calibrating and assigning estimated mean annual temperature and mean annual precipitation values to each forecast future climatic state. The locations of these present-day climate analogue sites are shown in Figure 5-22. Present-day climatic conditions at these sites are quantitatively consistent with those inferred for the forecasted future climate states, such as glacial-transition and monsoon states (Sharpe 2003, Section 6.3; BSC 2004g, Section 6.6). Present-day meteorological data for the lower-bound estimates were based on Station 4JA, located southeast of Yucca Mountain, while the upper-bound estimates were developed from a station in the northern area of the Nevada Test Site, Area 12 Mesa. Meteorological stations in Hobbs, New Mexico, and Nogales, Arizona, were selected to represent the upper-bound conditions for the monsoon climate state, while the current dry conditions at Yucca Mountain were used to represent the lower-bound conditions. For glacial-transition climates, three meteorological stations in eastern Washington were selected for the upper-bound conditions: Spokane, Rosalia, and St. John. The lower-bound glacial-transition climate conditions were established using meteorological data from stations in Delta, Utah, and Beowawe, Nevada (BSC 2004a, Section 6.5.4). SAR Section 2.3.1.2.3.1.2 provides further discussion of the basis for selecting these analogue meteorological stations.

Although future climate analyses (Sharpe 2003; BSC 2004g) contain different interpretations about the timing of future climate states, the differences are likely to be within the sampling error and other uncertainties, and the two sources are considered generally supportive of each other (BSC 2004a, Section 6.5.5.2).

5.2.5.5 Paleoclimatology and Climate-Related Processes Used to Estimate Postclosure Performance

The timing and nature of future climate states expected to occur during the next 10,000 years are important for predicting performance. Using an estimated rate of sediment accumulation from Owens Lake (SAR Section 2.3.1.2.3.1.1), the change from present-day climate to monsoon climate is set at 600 years in the future, and the duration of the monsoon climate is 1,400 years. At that time, 2,000 years in the future, the glacial-transition climate state occurs and lasts for the remaining 8,000 years of the 10,000 year period. This is the timing of climate change used in the TSPA (SAR Section 2.4). SAR Section 2.2 discusses the FEPs that are included in the process and abstraction models supporting the TSPA. Climate changes affect the unsaturated zone and saturated zone flow and transport models. Changes related to future climate states (monsoon and glacial transition) were evaluated but are not included in the biosphere model because it was determined that use of parameters representative of present-day biosphere characteristics (e.g., crop irrigation and overwatering rates, evaporation rate from fish ponds, and the proportion of the year people would use evaporative coolers) tend to overestimate radiation exposures of the RMEI for future, cooler and wetter climates. SAR Section 2.3.10 provides further discussion of the biosphere modeling approach.

With regard to the effects of future climates on unsaturated and saturated zone flow, the following conditions and processes are evaluated:

- Effects of climate change on infiltration and recharge, which could result in water table rise, perched water, and increased flux through the repository
- Potential for water table rise to alter flow and transport pathways in the unsaturated zone
- Potential for water table rise to alter flow and transport pathways in the saturated zone.

5.2.5.6 Developments in Meteorology and Climate Data and Models during Site Characterization

Meteorology—The meteorological investigations provided the atmospheric and meteorological data, including recurrence intervals for extreme weather phenomena, needed to calculate radiological doses from airborne releases from the repository and to design the repository surface facilities. The hydrometeorological measurements were also important inputs to hydrologic and climatic studies. Monitoring and testing results provide an adequate understanding of the meteorology of the Yucca Mountain site and the region to support preclosure and postclosure safety assessments. Present-day meteorological information was recorded and measured at meteorological stations within an approximate 40 km radius of Yucca Mountain, and this information was analyzed in *Data Analysis for Infiltration Modeling: Extracted Weather Station Data Used to Represent Present-Day and Potential Future Climate Conditions in the Vicinity of Yucca Mountain* (SNL 2006). Data collected from these meteorological stations were used to represent expected meteorological models for the present day scenario.

Climatology—Extensive studies characterizing the paleohydrology, paleoclimate, and present-day climates at and near Yucca Mountain have provided the information needed to forecast future climate changes that are expected during the next 10,000 years. Testing studies were conducted to characterize present-day climates in order to develop an understanding of the global and regional atmospheric factors influencing current climates to serve as a basis for modeling future climates. Paleoclimate studies of sedimentary deposits in dry lakes surrounding Yucca Mountain resulted in a thorough understanding of the sequence and nature of past climates. The range of variability to be expected in temperature and precipitation during the next 10,000 years has been established on the basis of these studies, and is used in predicting performance. See SAR Section 2.3.1.4 for details and conclusions of climatological studies.

The weather data analysis for infiltration modeling also evaluated meteorological data from seven proxy future-climate locations. The locations are Beowawe, Nevada; Delta, Utah; Hobbs, New Mexico; Nogales, Arizona; Rosalia, Washington; Spokane, Washington; and St. John, Washington. These proxy locations represent monsoon and glacial transition climatic conditions predicted to occur in the vicinity of Yucca Mountain during the next 10,000 years (BSC 2004g, Section 5, Table 6-1). Meteorological data from these proxy locations were also used for generating a suite of meteorological parameters to help understand present-day and future climate conditions, and their estimated uncertainties, in the vicinity of Yucca Mountain (SNL 2006, Section 7).

5.2.6 Overview of Reference Biosphere and the RMEI

As noted in Section 5.1.5.6, the biosphere is defined as the total ecosystem, including the organisms inhabiting it and the abiotic factors, such as climate, soil, surface waters, and air. The reference biosphere refers to a representation of the environment inhabited by a hypothetical receptor, the reasonably maximally exposed individual (RMEI), where that receptor is exposed to radionuclides released from the repository. The present-day characteristics of the Amargosa Valley area are used to describe the reference biosphere and the pathways by which radionuclides released into the environment would reach the RMEI. The present-day characteristics of the Amargosa Valley population are also used to describe the RMEI (SNL 2007f).

This section provides a description of the location and lifestyle of the RMEI, a description of biosphere transport and exposure pathways, a brief introduction to biosphere dose conversion factors, and a summary of biosphere conditions that are important to postclosure performance.

5.2.6.1 Location and Lifestyle of the RMEI

The Yucca Mountain reference biosphere is descriptive of the present environment downgradient in the “accessible environment” (10 CFR 63.302), which is beyond the postclosure controlled area of the Yucca Mountain Site, and is consistent with arid conditions. The site is located within the sparsely populated region at the southern edge of the transition zone between the Mojave Desert and the Great Basin in southern Nevada. The closest inhabitants live in the Town of Amargosa Valley at the intersection of U.S. Highway 95 and Nevada Route 373, a location formerly known as Lathrop Wells. This section discusses demographic information for the reference biosphere, including lifestyle and dietary habits representative of individuals living in the Amargosa Valley.

Climate—The regional climate is characterized by low precipitation, hot summers, cool winters, and low relative humidity (Section 5.2.5). The Sierra Nevada mountain range, a dominant feature in the region, is a major barrier to moist air moving east from the Pacific Ocean and creates a rain shadow. Annual average precipitation in the region ranges from 100 to 200 mm (4 to 8 inches), and decreases from higher to lower elevations. About 50% of the annual precipitation is from frontal storms during November through April. Precipitation during the summer months often occurs as localized thunderstorms that may create floods and runoff. Precipitation often varies between years by a factor of two. Temperatures vary through the year. Average maximum daytime temperatures are about 35°C (95°F) in July and 11°C (52°F) in January. Although the average nighttime temperature in January is above freezing, 2°C (36°F), freezing temperatures do occur. Low precipitation and warm temperatures keep atmospheric humidity low, with an annual average relative humidity of less than 20%. Section 5.2.5 contains more information on present day climate conditions.

Wind patterns in the region are strongly influenced by local topography and have a strong daily cycle, with winds from the south occurring during the day and winds from the north occurring at night. Seasonal wind patterns are common in the Yucca Mountain area. Summer months are marked by southerly winds, with speeds typically between 3.3 and 8.5 m/s. Northwest and north-northwest wind directions predominate in winter and spring, usually with speeds greater than 5.4 m/s. SAR Section 1.1.3 provides additional information on local meteorological and regional climatological extremes. SAR Section 2.3.10 discusses climate conditions used to develop parameters and to analyze biosphere pathways.

The air quality parameters for the reference biosphere are based on data from the monitoring sites at Yucca Mountain, and on data from analogue locations. Air-quality monitoring at Yucca Mountain between October 1991 and September 1995 consistently showed levels below the applicable National Ambient Air Quality Standards for gaseous criteria pollutants and particulate matter (DOE 2002b, Section 3.1.2.1).

Paleoclimatologic studies have been conducted in the region, and are summarized in Section 5.2.5 and SAR Section 2.3.1.

As noted, changes related to future climate states (monsoon and glacial transition) were evaluated but are not included in the biosphere model because it was determined that use of parameters representative of present-day biosphere characteristics (e.g., crop irrigation and overwatering rates, evaporation rate from fish ponds, and the proportion of the year people would use evaporative coolers) tend to overestimate radiation exposures of the RMEI for future, cooler and wetter climates.

Topography and Soils—The Yucca Mountain area, as well as most of Nevada, is characterized topographically by mountain ranges separated by intervening basins. These basins are filled with alluvial sediments. The region surrounding Yucca Mountain is drained by ephemeral stream channels, which feed into the Amargosa River and ultimately into Death Valley. There are no perennial streams in the region. The Amargosa Desert is a broad northwest-trending basin about 80 km long and up to 30 km wide, and is an important feature that encompasses the reference biosphere. The basin floor slopes gently to the southeast from elevations of about 975 m at the northern end, near Beatty, Nevada, to about 600 m toward the southern end (SNL 2007f, Section 6.1.1.1).

Currently, almost all agriculture in Amargosa Valley occurs in an area known as the “farming triangle,” which is more than 30 km from the geologic repository operations area (CRWMS M&O 1999a, Section 1). Soils within Amargosa Valley, including the area known as the Amargosa Farms farming triangle, are typically sandy to sandy-loam soils. The soils on alluvial fans and in stream channels in northern Amargosa Valley generally are deep and well to excessively drained. The surface soil layer generally is less than 20 cm (8 in.) thick and subsurface soils are up to 150 cm (59 in.) deep. Soil textures are very gravelly with fine sands to sandy loams. The soils are calcareous and moderately alkaline. Properties of the Amargosa Valley soils are described in Soil Survey of Nye County, Nevada, Southwest Part (USDA 2004, Parts I and II).

While existing Natural Resources Conservation Service information and site-specific data indicate that soils within the farming triangle and the areas at the edge of the accessible environment have similar characteristics (e.g., presence of root inhibiting layers, pH, and salts) that make them unsuitable for farming, farming has and is, nevertheless, occurring. It is concluded that soils are not the primary factor limiting agriculture between the farming triangle and the edge of the accessible environment. Economic considerations—such as the availability of water, availability of suitable cultivars, and demand for crops—will remain the important factors determining whether farming will occur north of the farming triangle (CRWMS M&O 1999a, Section 5). Soil characteristics are used to develop soil erosion and leaching rates, as well as parameters important to plant growth.

Water Resources—The hydrologic characteristics of the biosphere are strongly influenced by present-day climatic and geologic conditions. Low and infrequent rainfall, high evapotranspiration, and a deep water table are characteristic of this region, except for valley discharge areas, such as Ash Meadows National Wildlife Refuge. There are no perennial streams in the region. Episodic streamflow is a result of regional storms that occur mostly during the winter or localized thunderstorms that occur during the summer. The only wetland within this region is in the Ash Meadows National Wildlife Refuge, approximately 50 km southeast of Yucca Mountain, where groundwater discharges in a series of springs. The artificial impoundments of Crystal Reservoir, Lower Crystal Marsh, Horseshoe Reservoir, and Peterson Reservoir store discharge of springs in Ash Meadows. Fortymile Wash, a tributary of the Amargosa River, drains the area east of Yucca Mountain, and channels flow southeast along the western edge of the Amargosa Valley basin (BSC 2004a, Section 7.1.1). Figure 5-42 shows surface water features in the region.

Groundwater aquifers below Yucca Mountain and in the surrounding area flow generally south and west toward discharge areas in the Amargosa Desert and Death Valley. The aquifer of interest is in the Alkali Flat–Furnace Creek groundwater basin, centrally located in the Death Valley regional groundwater flow system (Figure 5-41) (BSC 2004a, Section 8.2). Regional groundwater quality sampling locations include wells in the central Amargosa Valley area (BSC 2004a, Section 8.2). Overall, the groundwater quality in the reference biosphere is generally good, and consistent with the State of Nevada description that most aquifers are suitable or marginally suitable for most uses (DOE 2002b, Section 3.1.4.2).

Water used for domestic, municipal, and agricultural purposes in Amargosa Valley comes from local groundwater wells. There are no public water-treatment systems in the Amargosa Valley (State of Nevada 1997).

Biological Resources—Native vegetation in the Yucca Mountain region is predominantly desert scrub and grasses. Four plant associations are found in wetter areas, such as at Ash Meadows and along the Amargosa River (CRWMS M&O 1999b, Sections 3.3.2 and 3.3.3). The native vegetation of the regional ecosystem is not an important characteristic contributing to potential exposure pathways in the reference biosphere.

Common spring-using, resident and transient mammals and birds are found within the vicinity of Yucca Mountain. The common species in the region are not contributors to pathway characteristics. Game bird species, such as Gambel's quail, chukar, and mourning dove, use some springs in the Ash Meadows area throughout the year. Some spring-dependent animals are protected within the boundaries of the Ash Meadows National Wildlife Refuge (CRWMS M&O 1999b, Sections 3.3.2 and 3.3.3). Hunting of quail, geese, ducks, coots, moorhens, snipe, doves and rabbit in accordance with State and refuge-specific regulations is allowed in designated areas of the refuge. Game species beyond protected areas are potential contributors to diet.

Demographics—The area around Yucca Mountain within approximately 80 km includes five counties: four in Nevada and Inyo County in California. Figure 5-23 illustrates the population distribution with the demographic study area. Population density within this area is very low. No permanent residents live within about 22 km of Yucca Mountain. Nye County, Nevada, as a whole, averages a population density of less than one person per square kilometer. The current locations of the irrigated fields and residences are spread over a large area around the Town of Amargosa Valley. The placement of irrigated areas and residences, spread over a large area around the town of Amargosa Valley, are not random, but are determined (in part) by such things as federal land ownership and soil qualities. The fields and residences are distributed in clusters within this area. Using the location of irrigated areas, residences, and wells, there is a clearly defined community boundary that includes essentially all residences and irrigated areas. The clearly defined community area excludes the Ash Meadows and Highway 95 areas. In some parts, there is a large space with no fields and residences between these clusters.

The closest inhabitants to Yucca Mountain live about 22 km away, in the northern Amargosa Valley near the intersection of U.S. Highway 95 and Nevada State Route 373. In recent years, there have been about six to seven households at this location. This area is near the location of the hypothetical community represented by the RMEI, which is located at the boundary of the accessible environment, approximately 18 km downstream of the repository. The Amargosa Farms area, about 10 to 15 km south-southwest of the Lathrop Wells intersection, is the closest agricultural area (Figure 5-45). There is a small general store, a community center, a senior center, a library, a small medical clinic, an elementary school, a restaurant, a hotel casino, and a motel in the Amargosa Valley. The nearest movie theaters, larger stores, other restaurants, and hospitals are in Pahrump, Nevada, and Las Vegas, Nevada, about 84 km and 130 km from Yucca Mountain, respectively (SAR Section 2.3.10.2.1).

The Amargosa Valley is sparsely populated and supports a population of about 1,412 people (SAR Section 1.1.2.1). Approximately 2,000 acres are commercially farmed. More than 90% of the acreage is planted in alfalfa or other hay. Small grains, pistachios, grapes, orchard crops, garlic, and onions are also commercially grown. There is a dairy with more than 5,000 cows. Gardening in small vegetable plots and animal husbandry, including the management of a few cattle, sheep, chickens, and other farm animals, are common (SNL 2007f, Section 6.1.1.3). SAR Section 2.3.10 discusses the population demographics important to understanding potential exposure pathways and to developing parameters for the biosphere model.

Characteristics of the RMEI—10 CFR 63.312 states that: The RMEI is a hypothetical person who meets the following criteria:

> (a) Lives in the accessible environment above the highest concentration of radionuclides in the plume of contamination.
>
> (b) Has a diet and living style representative of the people who now reside in the Town of Amargosa Valley, Nevada. DOE must use projections based upon surveys of the people residing in the Town of Amargosa Valley, Nevada, to determine their current diets and living styles and use the mean values of these factors in the assessments conducted for §§ 63.311 and 63.321.

(c) Uses well water with average concentrations of radionuclides based on an annual water demand of 3,000 acre-feet.

(d) Drinks 2 liters of water per day from wells drilled into the groundwater at the location specified in paragraph (a) of this section.

(e) Is an adult with metabolic and physiological considerations consistent with present knowledge of adults.

As such, the RMEI is a hypothetical receptor who is modeled based on a small community with characteristics of the Amargosa Valley population. The RMEI does not represent any individual; rather, the RMEI is representative of the community as a whole. This hypothetical individual is located at the southernmost boundary of the postclosure controlled area at 36° 40′ 13.6661″ North latitude at the point where the potentially contaminated groundwater enters the accessible environment (BSC 2005b, Section 6.1). Diet and lifestyle information for the residents of the Amargosa Valley is used to characterize the RMEI. Residents in the area consume some locally produced food, such as vegetables, fruit, grain, meat, poultry, fish, eggs, and milk. In general, locally produced foods comprise a small portion of the total diet (BSC 2005b, Section 6.4). Just under half of the Amargosa Valley residents surveyed had gardens (SNL 2007f, Section 6.1.2). SAR Section 2.3.10.2.2 provides additional dietary and lifestyle information characterizing the RMEI.

5.2.6.2 Summary of Biosphere Pathways

The reference biosphere is used to model the environmental transport of radionuclides released from the repository, along with the RMEI exposure to these radionuclides. Biosphere transport and exposure pathways are determined by the type of interface between the geosphere and the biosphere, and the site-specific conditions in the reference biosphere, including the lifestyle of the people living in Amargosa Valley. Based on this approach, six environmental media that could result in radionuclide exposure are evaluated. Those environmental media are well water (groundwater), surface soil, air, plants, animals, and fish (SNL 2007f, Section 6.13.4). Figure 5-46 provides a conceptual illustration of the biosphere setting.

There are two potential means of radionuclide release from the repository into the accessible environment. The first is through groundwater from wells. Exposure pathways are defined by the use of that water, including drinking water, irrigation of commercial and garden crops, livestock watering, fish farms, and the use of evaporative coolers. Another potential means would be through volcanic ash in the event of an eruption that intersected the repository. Separate exposure scenarios were developed for these two radionuclide release scenarios, because the transport mechanisms differ.

Groundwater Release—The groundwater exposure scenario considers radionuclides entering the biosphere. The model includes use of that groundwater for drinking, crop and garden irrigation, livestock watering, fish farms, and use of evaporative coolers. Irrigation could result in radionuclide transport to topsoil and crops. Radionuclide-affected soil could be resuspended and deposited on crops, inhaled by the RMEI, and inadvertently ingested by the RMEI and farm animals. Radioactive gases escaping from the soil could also be taken up by crops and inhaled by the RMEI. The crops could be eaten by the RMEI and fed to farm animals. Products from those farm animals (i.e., eggs, milk, and meat) and fish could also be eaten by the RMEI. To include the consequences of these pathways, the RMEI dose for this exposure scenario included contributions from external exposure to soil; inhaling resuspended soil; aerosols from evaporative coolers; radioactive gases and their decay products; and ingesting water, crops, fish, animal products, and soil (SAR Section 2.3.10.2.5).

Volcanic Release—The volcanic ash exposure scenario considers radionuclides that could be deposited within the reference biosphere by deposition or redistribution of ash and associated radionuclides following a volcanic eruption through the repository. The model considers transport of radionuclides from the ash to soil, air, crops, and animal products. Radionuclide transport to crops could arise from deposition of resuspended particles of ash and from uptake through roots. Farm animals could be fed those crops and ingest radionuclide-affected soil. The RMEI could receive a dose from external exposure to soil; from inhaling resuspended ash and ^{222}Rn decay products; and from ingesting crops, animal products, and soil. Pathways and environmental media related to radionuclides in groundwater (e.g., farm-raised fish) were not considered in this exposure scenario (SAR Section 2.3.10.2.6).

SAR Section 2.3.10 provides additional discussion of the exposure scenarios, environmental media, exposure modes, and exposure and transport pathways important to performance of the repository.

5.2.6.3 Summary of Biosphere Dose Conversion Factors

The environmental radiation model for Yucca Mountain (the biosphere model) is used to track the environmental transport of radionuclides through the biosphere, and to calculate the annual dose to the RMEI per unit of radionuclide concentration in groundwater or soil mixed with volcanic ash. The primary outputs of the biosphere model are sets of biosphere dose conversion factors, equivalent to the annual dose from all potential exposure pathways that the RMEI would experience as a result of a unit concentration of a radionuclide in groundwater (SAR Section 2.3.10.5.1) or volcanic ash (SAR Section 2.3.10.5.2). The biosphere component of the TSPA model combines the biosphere dose conversion factors with estimates of radionuclide concentrations in groundwater and volcanic ash from the saturated zone transport abstraction models and the models that predict transport of radionuclides released during a volcanic eruption. These data are used to calculate the predicted annual total dose at the RMEI location to evaluate compliance with the individual protection standard in proposed 10 CFR 63.311. SAR Section 2.3.10 provides additional discussion of the biosphere model and biosphere dose conversion factors.

5.2.6.4 Biosphere FEPs Used to Estimate Postclosure Performance

FEPs that describe the biosphere system and associated chemical, physical, and biological processes and that are consistent with present knowledge of the conditions in the region surrounding Yucca Mountain were the fundamental elements used to develop the conceptual model of the biosphere (SNL 2007f, Section 6.2). SAR Section 2.2 provides a complete list of FEPs, both included and excluded from the TSPA. The biosphere-related FEPs were evaluated using the characterization information for the reference biosphere, the RMEI, the associated biosphere transport and exposure pathways, and the regulatory requirements. The processes that would transport radionuclides to environmental media and the pathways by which the RMEI would be exposed to radionuclides in those media were evaluated. The processes identified were used to develop an interaction matrix of radionuclide transfer and exposure pathways that were included in the TSPA (SNL 2007f, Section 6.3).

Among the types of FEPs included are climate change, water management, and land use activities, soil characteristics, precipitation, biosphere characteristics, human characteristics and lifestyle, atmospheric transport, radioactive decay and ingrowth, food and animal uptake, and farms and fisheries (SNL 2007f, Section 6.2). The biosphere FEPs are included in the TSPA through the biosphere dose conversion factors (SNL 2007f, Section 6.2).

5.2.6.5 Developments in Biosphere Data and Models during Site Characterization

A TSPA performed in the late 1990s was the first to incorporate an all-pathway biosphere dose conversion factor. There was no regulatory guidance for the reference biosphere or the receptor at that time. Subsequently, the regulatory environment changed, and at the time of the DOE site recommendation in 2002, 10 CFR Part 63 had been finalized. The reference biosphere and the RMEI, as characterized for the present biosphere model, are consistent with present knowledge of the Yucca Mountain region, as constrained by the regulatory requirements of proposed 10 CFR Part 63. SAR Section 2.3.10 provides additional discussion of the biosphere.

5.3 GENERAL REFERENCES

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Table 5-1. Approaches and Main Activities of Unsaturated Zone Testing

Testing Approaches	**Testing Activities Described in Section(s) of *In Situ Field Testing of Processes***
Air injection tests along boreholes	Air-permeability distributions and excavation-induced enhancements (Section 6.1) Cross-hole connectivity (Section 6.5) Systematic hydrologic characterization (Section 6.11)
Liquid release tests from borehole intervals	Seepage into drift (Section 6.2) Tracer-migration delineation (Section 6.3) Fracture-matrix interaction (Section 6.6) Fault and matrix flow (Section 6.7) Systematic hydrologic characterization (Section 6.11) Drift-to-drift flow and transport (Section 6.12) Busted Butte transport test (Section 6.13)
Moisture monitoring (relative humidity, temperature) and evaporation measurements	Seepage into drift (Section 6.2) Moisture monitoring and bulkhead study (Section 6.10) Systematic hydrologic characterization (Section 6.11)
Wetting front monitoring and potential measurements	Fracture-matrix interaction (Section 6.6) Fault and matrix flow (Section 6.7) Construction water migration (Section 6.9) Drift-to-drift flow and transport (Section 6.12)
Laboratory hydrologic measurements of rock and water samples	Tracer penetration and water imbibition (Section 6.4) Systematic hydrologic characterization (Section 6.11) Busted Butte transport test (Section 6.13)
Laboratory hydrochemical measurements of rock and water samples	Tracer-migration delineation (Section 6.3) Tracer penetration and water imbibition (Section 6.4) Fracture-matrix interaction (Section 6.6) Construction water migration (Section 6.9) Moisture monitoring and bulkhead study (Section 6.10) Busted Butte transport test (Section 6.13) Geochemical and isotopic observations (Section 6.14)
Laboratory isotopic measurements of rock and water samples	Moisture monitoring and bulkhead study (Section 6.10) Geochemical and isotopic observations (Section 6.14)

Source: BSC 2004e, Table 1-1.

Table 5-2. Unsaturated Zone Testing at Different Locations

Testing Activity Described in Indicated Section(s)	**Alcove**					**Niche**					**Drift**				
						3566	**3650**	**3107**	**4788**	**CD 1620**	**ESF**			**ECRB Cross -Drift**	**Busted Butte**
	1	**4**	**6**	**7**	**8**	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**North Ramp**	**Main Drift**	**South Ramp**		
Air–Permeability	X	X	X	—	X	X	X	X	X	X	—	—	—	X	X
Liquid Observation	—	—	—	—	—	X	—	—	—	—	—	—	—	X	—
Dyed Flow Path	—	—	—	—	—	X	X	X	X	—	—	—	—	—	X
Seepage Threshold	X	—	—	—	—	—	X	X	X	X	—	—	—	X	—
Liquid Release	X	X	X	—	X	—	X	X	X	X	—	—	—	X	X
Evaporation Measurement	—	—	—	—	—	—	—	X	X	X	—	—	—	X	—
Wetting Front/Potential	—	X	X	—	—	X	—	X	—	—	X	X	X	X	—
Moisture Monitoring	—	—	—	—	—	X	—	X	X	X	X	X	X	X	—
Geophysical Tomography	—	—	—	—	X	—	—	X	—	—	—	—	—	—	X
Lab Hydrology	—	—	X	X	—	X	X	—	X	—	—	—	—	X	X
Tracer Analysis	—	—	—	—	—	—	X	X	X	—	—	—	—	—	X
Geochemistry	—	—	X	X	—	—	—	—	—	—	X	X	X	X	—
Isotopic Analysis	—	—	X	X	—	X	—	—	—	—	X	X	X	X	—

Source: BSC 2004e, Table 1-2.

Table 5-3. Generalized Stratigraphic Column of Tertiary Volcanic Rocks in the Vicinity of Yucca Mountain

Group	Formation/Unit		Thickness in Vicinity of Yucca Mountain (m)	General Lithology	Correlative Units	
					Hydrogeologic	Thermal-mechanical
Timber Mountain	Ammonia Tanks Tuff		Not present over the repository footprint	Welded to nonwelded rhyolite tuff	Unconsolidated surficial material	Undifferentiated overburden
	Rainier Mesa Tuff		Generally <30	High-silica rhyolite and quartz latite tuffs		
	Pre-Rainier Mesa Tuff bedded tuff		17	Nonlithified pyroclastic-flow deposits		
Paintbrush	Rhyolite of Comb Peak		≤130	Rhyolite lava flows and related tephra; pyroclastic-flow deposits		
	Tuff Unit “X”		6-23			
	Rhyolite of Vent Pass		0-150			
	Post-Tiva Canyon Tuff bedded tuff		<2-4.5	Pyroclastic-flow and fallout tephra deposits		
	Tiva Canyon Tuff	Crystal-rich member	<50-175	Compositionally zoned (rhyolite to quartz latite) tuff sequence; each member divided into several zones and subzones	_____ a _____ Tiva Canyon welded _____ b _____	_____ a _____ Tiva Canyon welded _____ b _____
		Crystal-poor member				
	Pre-Tiva Canyon Tuff bedded tuff		<1-3	Pyroclastic fallout tephra deposits with thin weathered zones		

Table 5-3. Generalized Stratigraphic Column of Tertiary Volcanic Rocks in the Vicinity of Yucca Mountain (Continued)

Group	Formation/Unit		Thickness in Vicinity of Yucca Mountain (m)	General Lithology	Correlative Units	
					Hydrogeologic	**Thermal-mechanical**
Paintbrush (Continued)	Yucca Mountain Tuff		0-55	Nonwelded to densely welded pyroclastic-flow deposit	Paintbrush Tuff nonwelded (PTn)	Paintbrush Tuff nonwelded (PTn)
	Rhyolite of Black Glass Canyon		2-14	Rhyolite lava flows and related tephra		
	Rhyolite of Delirium Canyon		≤250 (lava) ≤100 (ash flows)			
	Rhyolite of Zig Zag Hill		≤10			
	Pre-Yucca Mountain Tuff bedded tuff		<1-46	Nonwelded pyroclastic-flow deposits		
	Pah Canyon Tuff		0-79	Pyroclastic-flow deposits; abundant large pumice clasts		
	Pre-Pah Canyon Tuff bedded tuff		3-10	Vitric to devitrified and altered fallout tephra and ash-flow tuff		
	Topopah Spring Tuff	Crystal-rich member	0-381	Compositionally zoned (rhyolite to quartz latite) tuff sequence; each member divided into Repository host rock is within crystal-poor member.	_____ c _____ Topopah Spring welded ____ d _____	_____ c _____ Topopah Spring welded ____ d _____
		Crystal-poor member				
	Pre-Topopah Spring Tuff bedded tuff		0-17	Bedded tuffaceous deposits		
—	Calico Hills Formation		15-457	Rhyolite tuffs and lavas; contains five pyroclastic units	Calico Hills nonwelded	Calico Hills and lower Paintbrush nonwelded
	Pre-Calico Hills Formation bedded tuff		9-39	Pyroclastic-flow and coarse-grained fallout deposits		

Table 5-3. Generalized Stratigraphic Column of Tertiary Volcanic Rocks in the Vicinity of Yucca Mountain (Continued)

Group	Formation/Unit	Thickness in Vicinity of Yucca Mountain (m)	General Lithology	Correlative Units	
				Hydrogeologic	Thermal-mechanical
Crater Flat	Prow Pass Tuff	15-194	Includes four variably welded pyroclastic-flow deposits	Calico Hills nonwelded or Crater Flat unit	_____ e _____ Prow Pass welded
	Pre-Prow Pass Tuff bedded tuff	<1-3.5	Pumiceous tuffs and pyroclastic-flow deposits		Upper Crater flat nonwelded
	Bullfrog Tuff	15-366	Includes two pyroclastic-flow deposits separated by a pumiceous fallout unit		Bullfrog welded
	Pre-Bullfrog tuff bedded tuff	6-11	Pyroclastic-flow deposits within thin zones of fallout tephra		Middle Crater Flat nonwelded
	Tram Tuff	0-370	Pyroclastic-flow deposits and bedded tuffs		Tram welded
	Pre-Tram Tuff bedded tuff	0-21	Pyroclastic-flow and fallout deposits	Units not defined	Units not defined
—	Dacitic lava and flow breccia	111-249	Dacitic lavas and flow breccia; bedded tuff at base		
	Lithic Ridge Tuff	185-304	Pyroclastic-flow deposit		
	Pre-Lithic Ridge Tuff volcanic rocks	45-350+	Pyroclastic-flow deposits and bedded tuffs		

NOTE: Dashes in the Group column indicate that the Formation/Unit is not associated with a named group. Labeled Stratigraphic Horizons:

[a] Contact between moderately welded (above) and densely welded (below) subzones in the vitric zone of the crystal-rich member of the Tiva Canyon Tuff.

[b] Contact between lower nonlithophysal (above) and vitric (below) zones of the crystal-poor member of the Tiva Canyon Tuff.

[c] Contact between moderately welded (above) and densely welded (below) sub zones of the vitric zone of the crystal-rich member of the Topopah Spring Tuff.

[d] Contact between densely welded (above) and moderately welded (below) subzones of the vitric zone of the crystal-poor member of the Topopah Spring Tuff; coincides closely with “vitric-zeolitic” boundary mentioned in text.

[e] Contact between pyroxene-rich (above) and welded pyroclastic-flow deposits (below) in upper part of the Prow Pass Tuff.

Source: Stuckless and Levich 2007, pp. 60 to 61, Table 1

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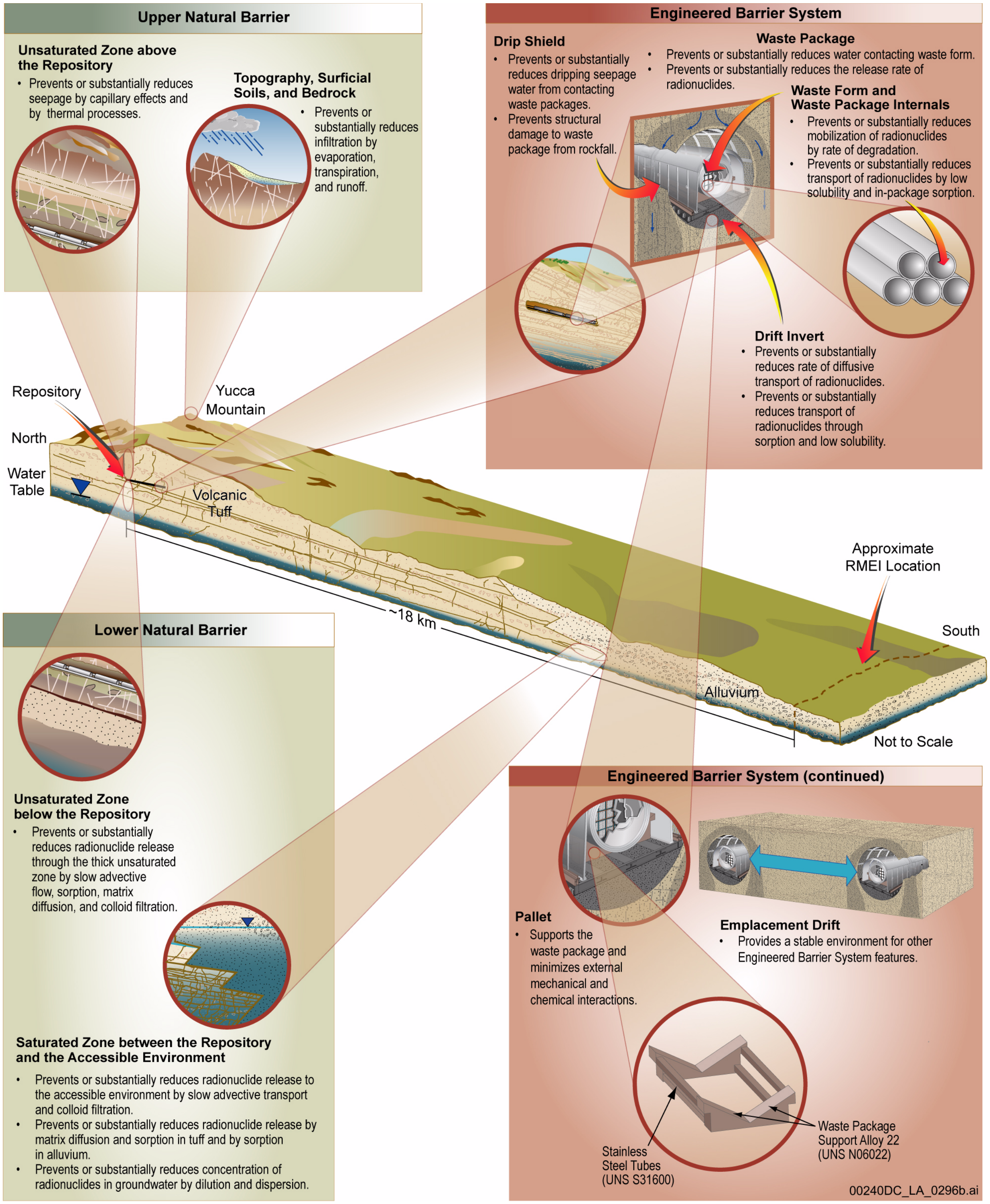

Upper Natural Barrier

Unsaturated Zone above the Repository

- Prevents or substantially reduces seepage by capillary effects and by thermal processes.

Topography, Surficial Soils, and Bedrock

- Prevents or substantially reduces infiltration by evaporation, transpiration, and runoff.

Engineered Barrier System

Drip Shield

- Prevents or substantially reduces dripping seepage water from contacting waste packages.
- Prevents structural damage to waste package from rockfall.

Waste Package

- Prevents or substantially reduces water contacting waste form.
- Prevents or substantially reduces the release rate of radionuclides.

Waste Form and Waste Package Internals

- Prevents or substantially reduces mobilization of radionuclides by rate of degradation.
- Prevents or substantially reduces transport of radionuclides by low solubility and in-package sorption.

Drift Invert

- Prevents or substantially reduces rate of diffusive transport of radionuclides.
- Prevents or substantially reduces transport of radionuclides through sorption and low solubility.

Lower Natural Barrier

Unsaturated Zone below the Repository

- Prevents or substantially reduces radionuclide release through the thick unsaturated zone by slow advective flow, sorption, matrix diffusion, and colloid filtration.

Saturated Zone between the Repository and the Accessible Environment

- Prevents or substantially reduces radionuclide release to the accessible environment by slow advective transport and colloid filtration.
- Prevents or substantially reduces radionuclide release by matrix diffusion and sorption in tuff and by sorption in alluvium.
- Prevents or substantially reduces concentration of radionuclides in groundwater by dilution and dispersion.

Engineered Barrier System (continued)

Pallet

- Supports the waste package and minimizes external mechanical and chemical interactions.

Emplacement Drift

- Provides a stable environment for other Engineered Barrier System features.

Figure 5-1. Schematic Illustration of the Multiple Barrier Repository System

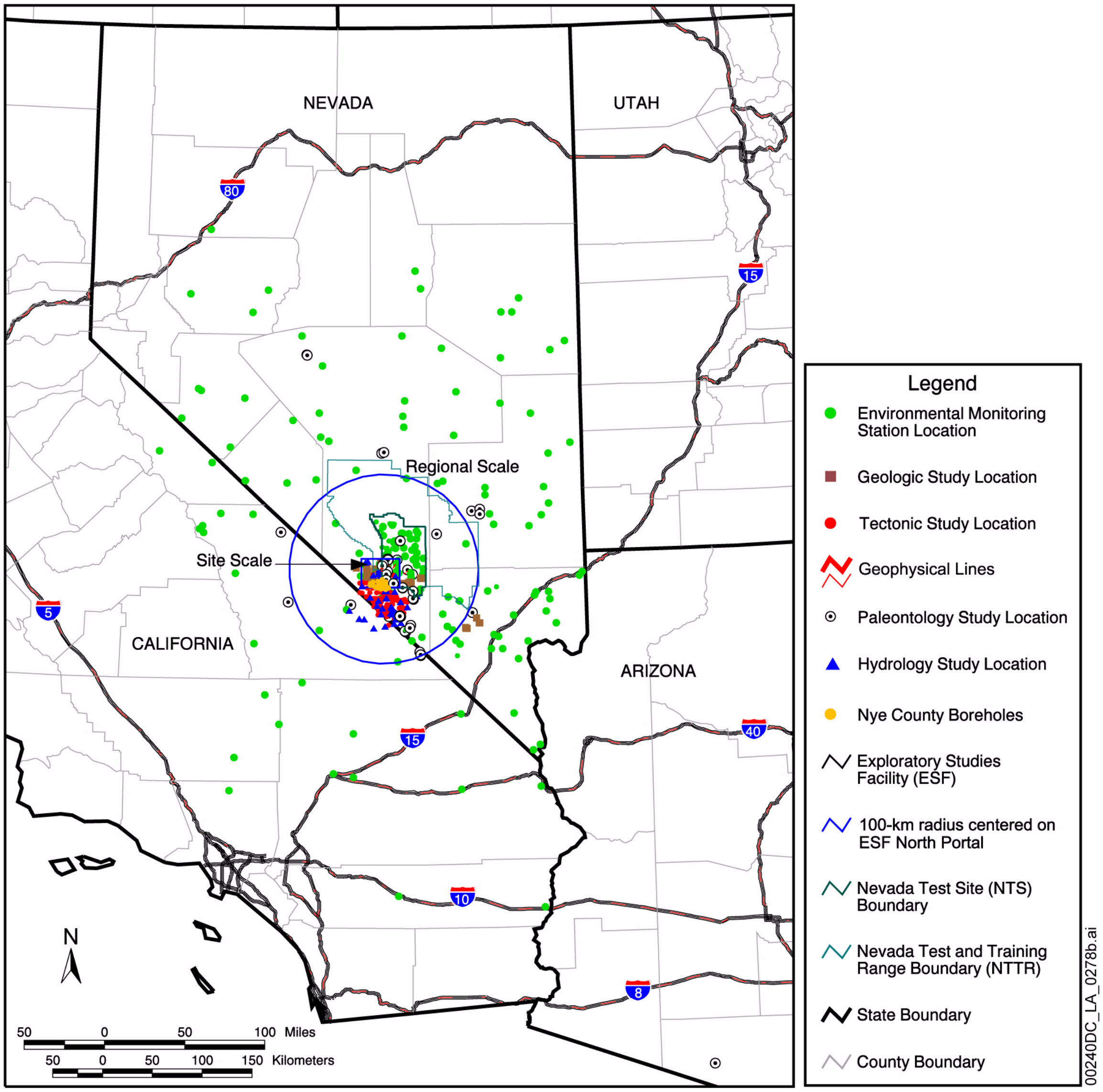

Figure 5-2. Map Showing Exploration, Monitoring, and Characterization Locations Used for the Yucca Mountain Evaluation

NOTE: Expanded views of the regional scale and site scale are provided in Figures 5-3 and 5-4, respectively.

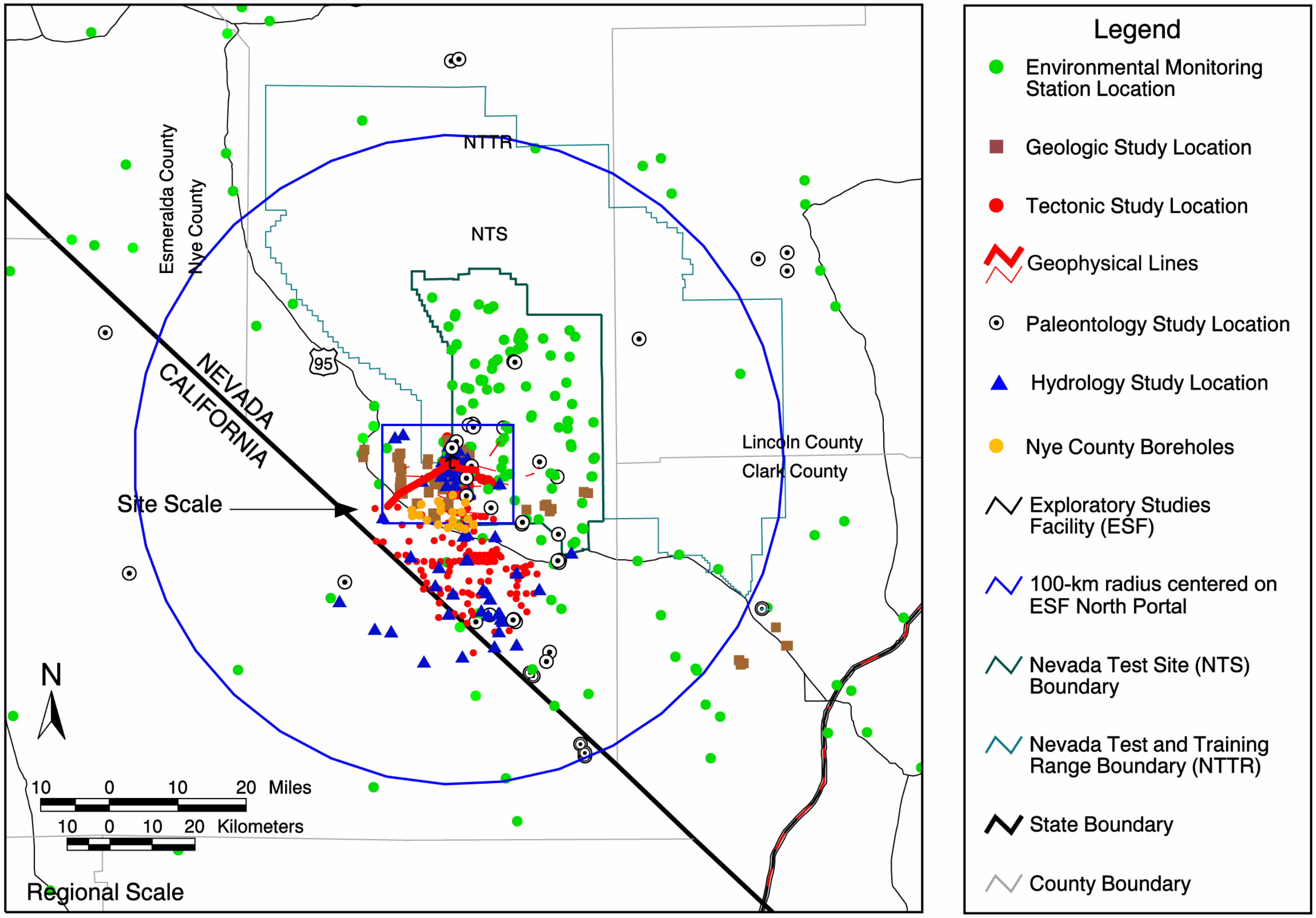

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Figure 5-3. Map Showing Exploration, Monitoring, and Characterization Locations Used for the Yucca Mountain Evaluation

NOTE: Expanded view of the site scale is provided in Figure 5-4.

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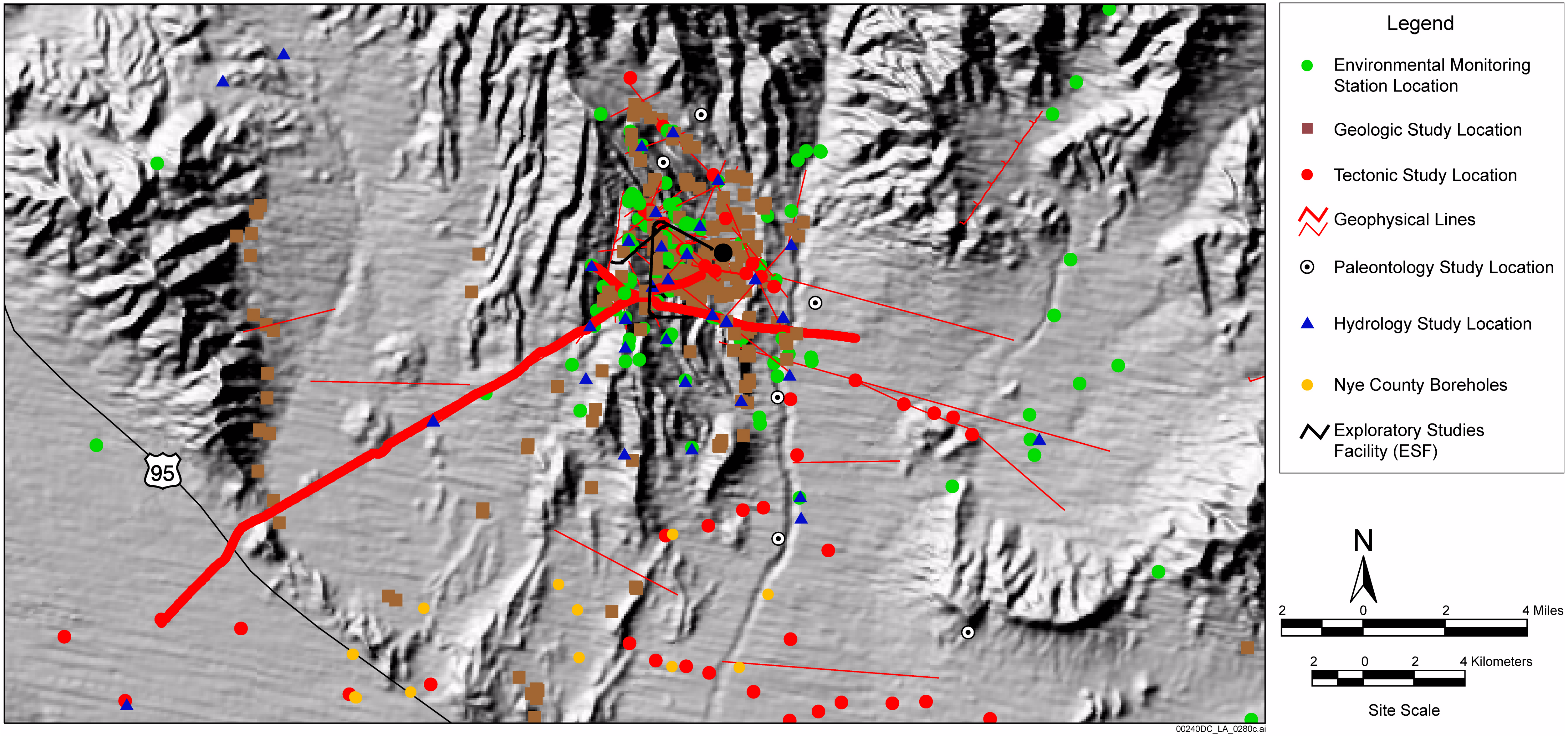

Figure 5-4. Map Showing Exploration, Monitoring, and Characterization Locations Used for the Yucca Mountain Evaluation

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Figure 5-5. View of Exploratory Studies Facility at the North Ramp Turn

NOTE: Exposure is Tptpul at location of photograph.

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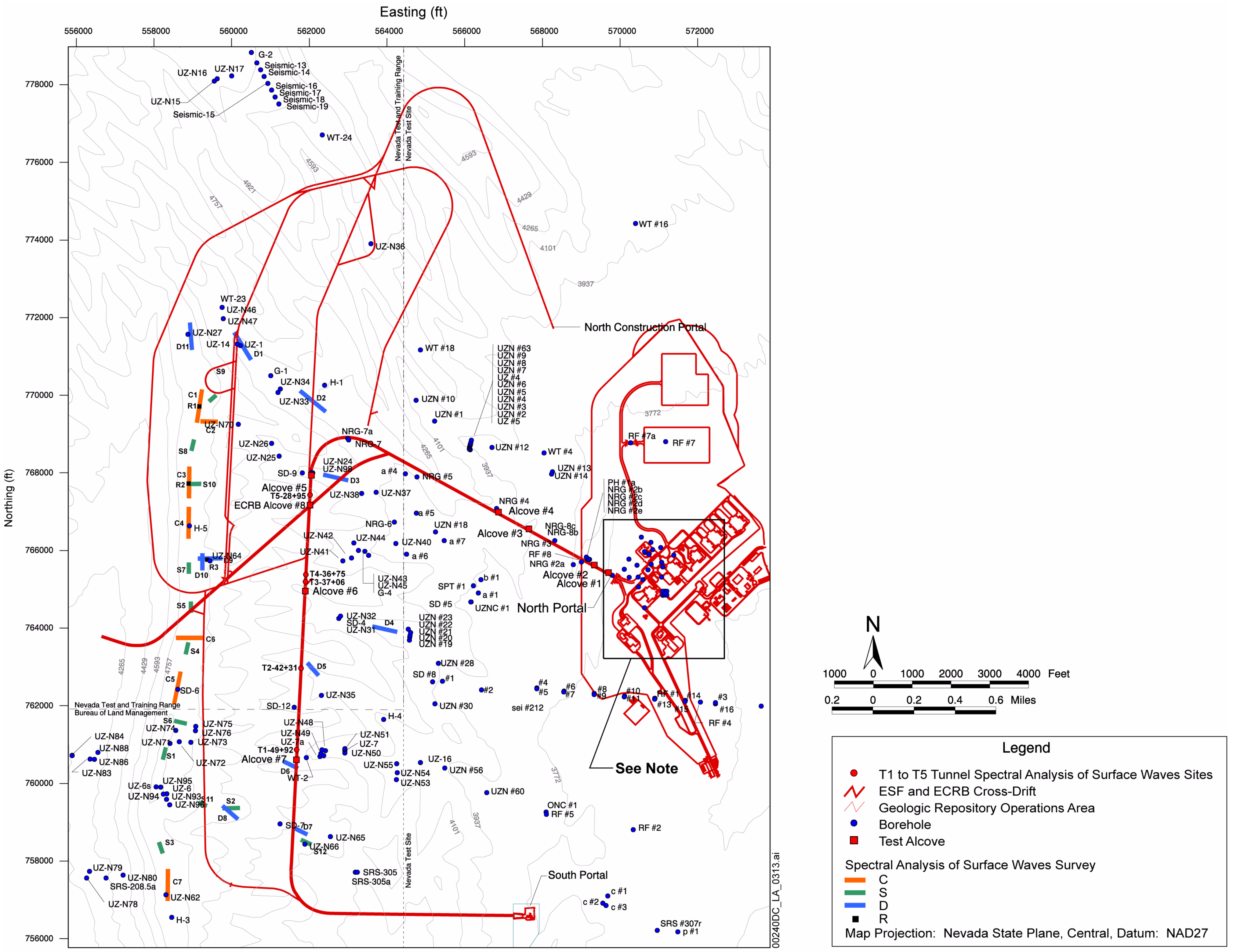

NOTE: Area is shown in detail in SAR Figures 1.1-141 and 1.1-145.

Source: BSC 2002a, Figures 144 and 157; BSC 2005c, Figure I-1.

Figure 5-6. Locations of Exploration Relative to Exploratory Studies Facility and Repository

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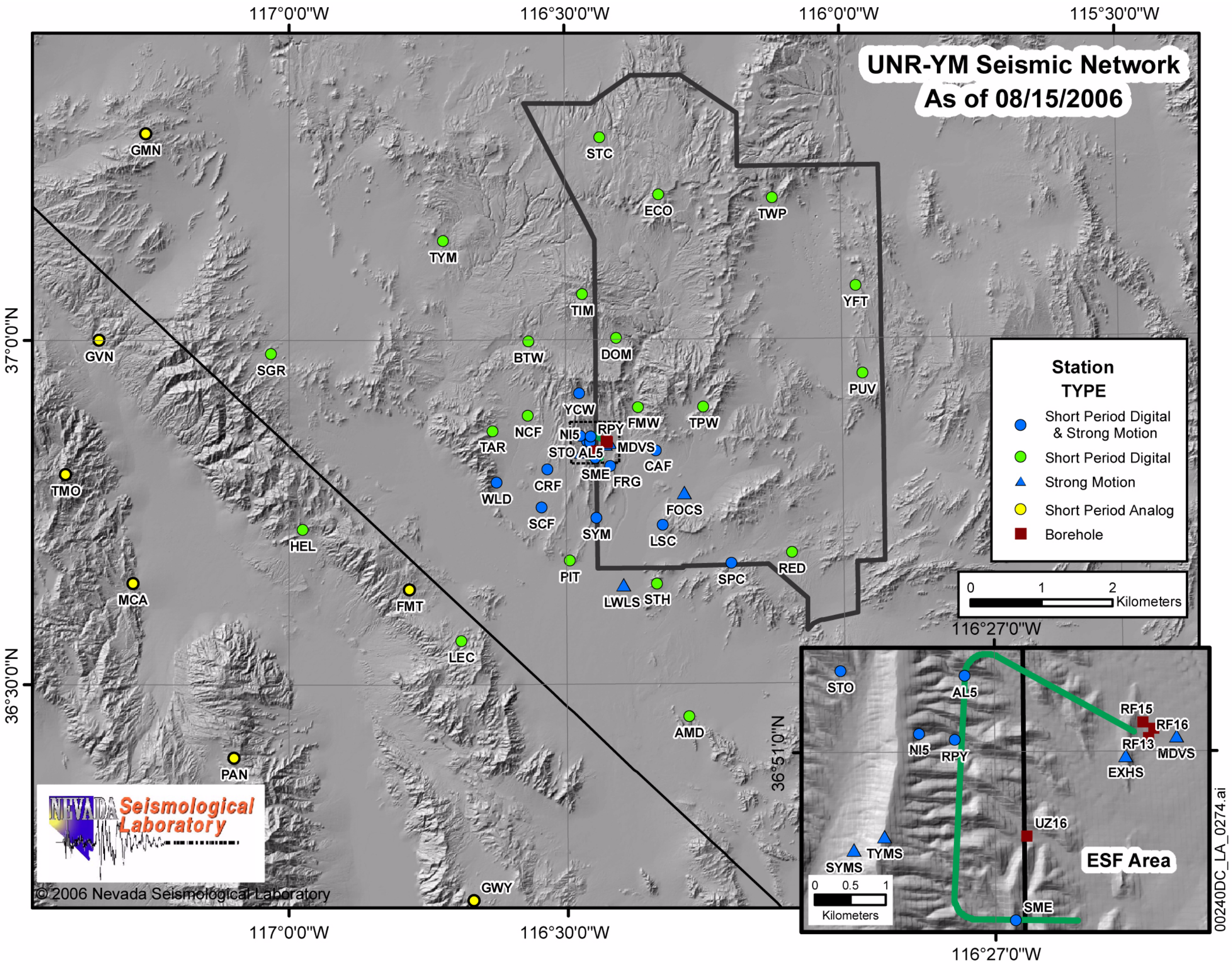

Figure 5-7. Southern Great Basin Digital Seismic Network and Contributing Seismic Monitoring Station Locations

NOTE: Nevada Test Site boundary is shown for illustration purposes only.

Source: Nevada Seismological Laboratory 2006.

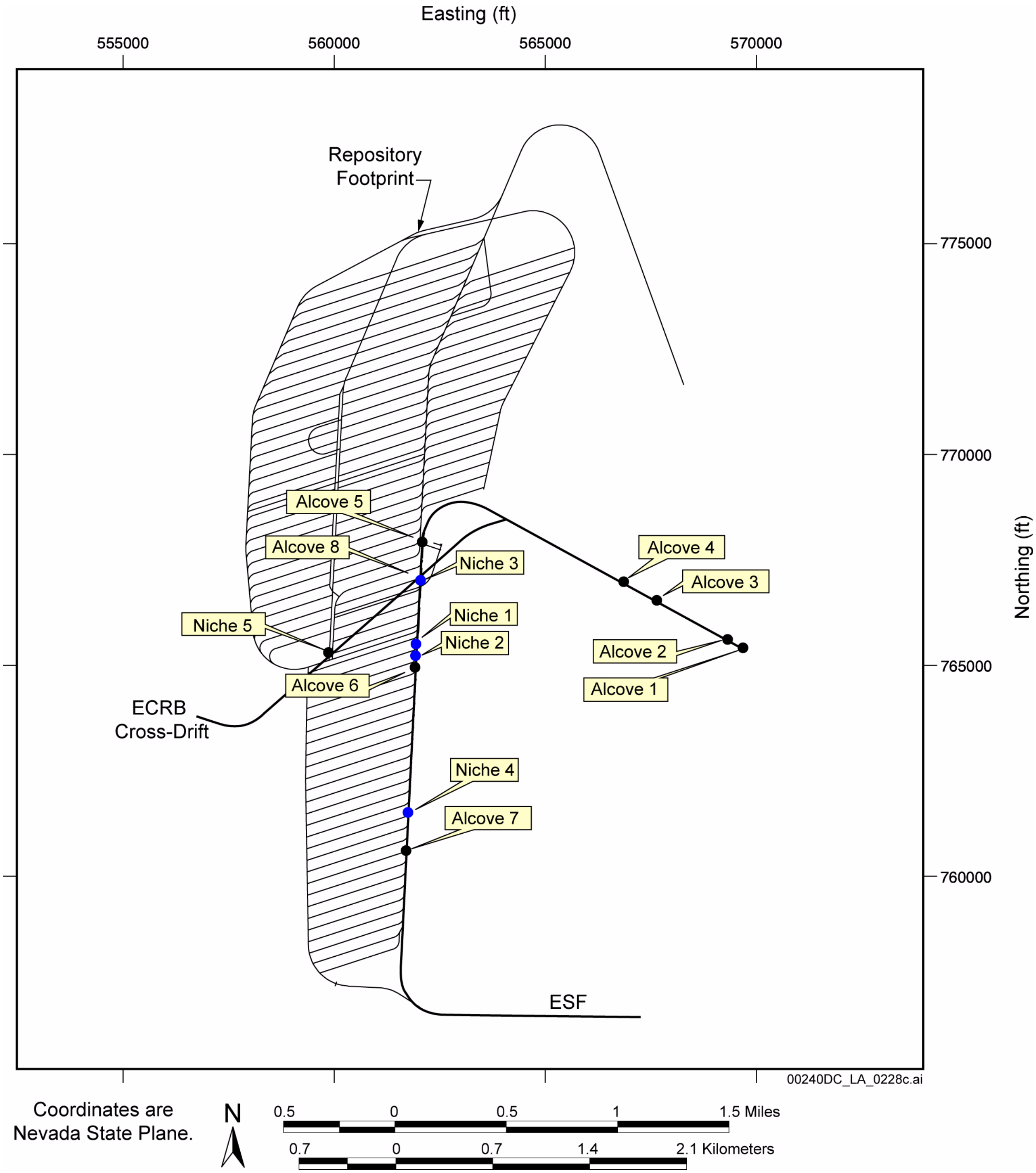

Figure 5-8. Map Showing Locations of Testing Alcoves and Niches in the Exploratory Studies Facility and the Enhanced Characterization of the Repository Block Cross-Drift

Source: BSC 2004a, pp. 3-20 and 7-2; BSC 2004e, Figure 1-2.

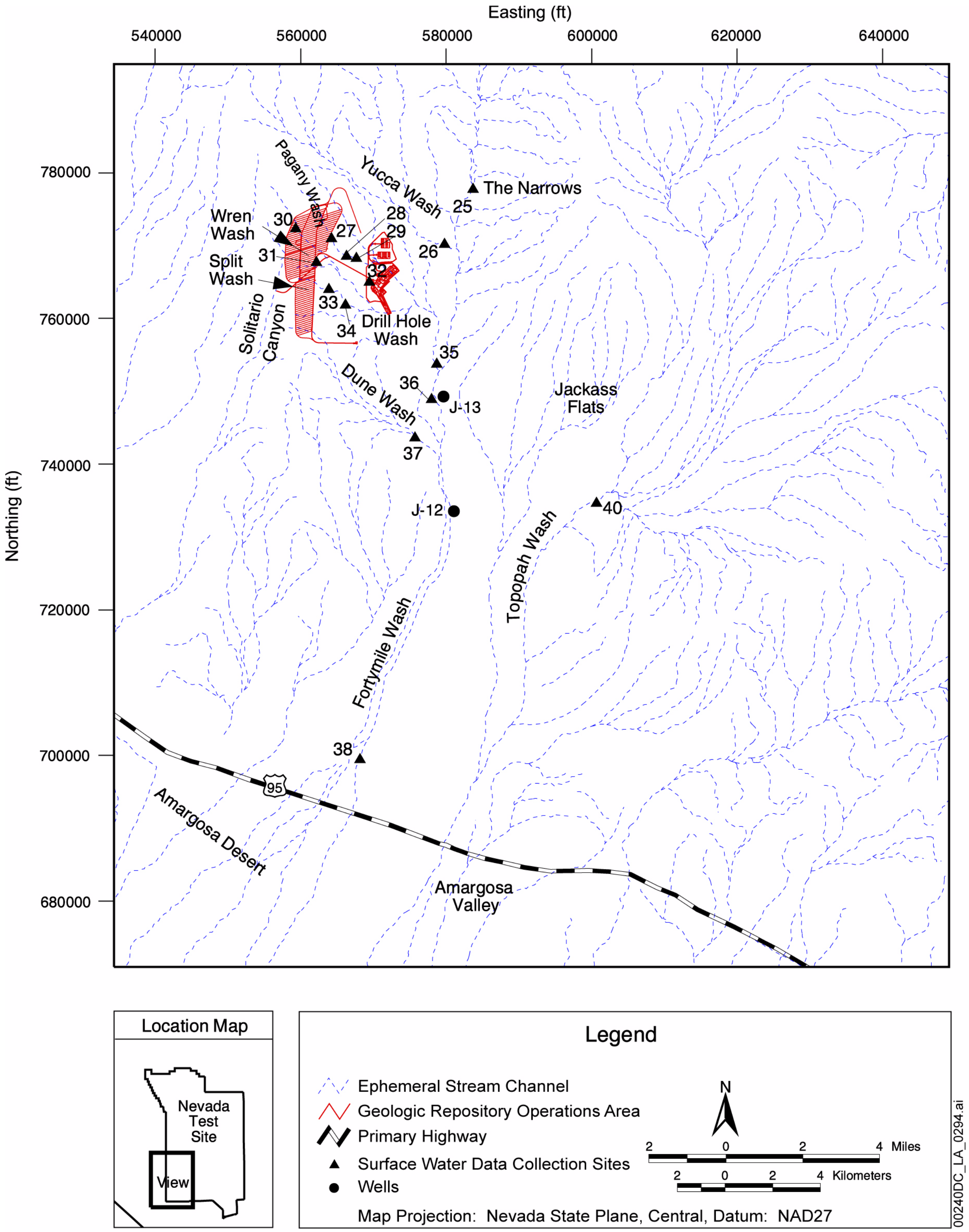

Figure 5-9. Surface Water Data Collection Sites in the Yucca Mountain Vicinity

NOTE: The geologic repository operations area is shown for illustration purposes only.

Source: BSC 2004a, modified from Figure 7-5b.

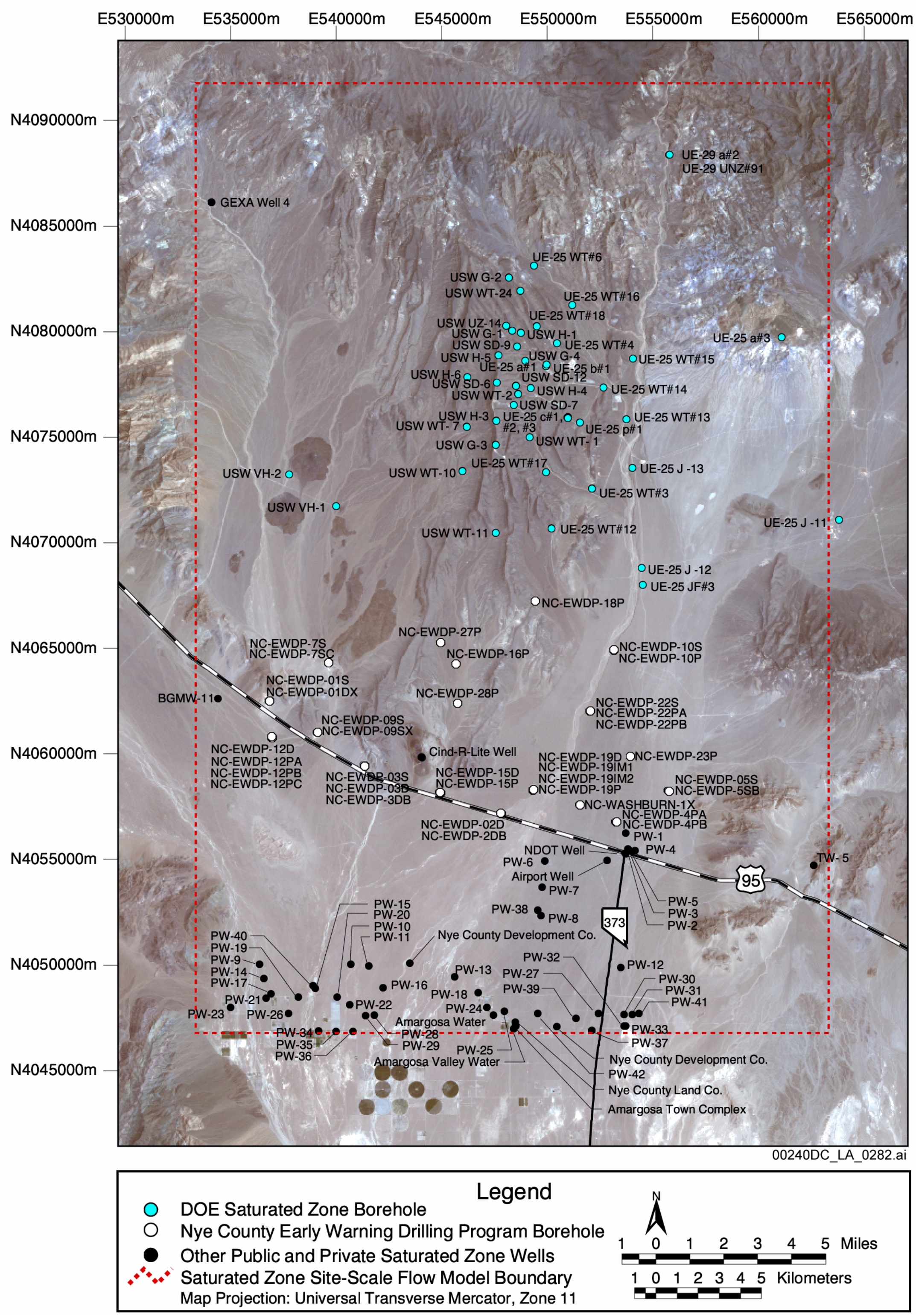

Figure 5-10. Location of Boreholes Used to Characterize the Potentiometric Surface in the Yucca Mountain Area

Source: BSC 2004d, Figure 1-2.