CHAPTER 7

CURRENT INFORMATION CONCERNING A POTENTIAL WASTE REPOSITORY AT YUCCA MOUNTAIN

7.1 PRINCIPAL FEATURES OF THE NATURAL ENVIRONMENT

This section describes the principal features of the natural environment at Yucca Mountain and the surrounding area. This information is based primarily on the site characterization work of the Department of Energy (DOE). Particular emphasis is given to those aspects of the geology, mineralogy, structure, hydrology, and climate of the site that are most likely to affect the performance of a high-level waste repository. The glossary of technical terms at the end of this BID should be helpful to the reader.

7.1.1 Geologic Features

A description of the important features of Yucca Mountain and the surrounding area provides a picture of the geologic setting that serves as the context for understanding the repository design. Important aspects of the geology around the site, such as the presence of faults, seismicity, and the nature and distribution of rock types, are discussed.

7.1.1.1 Location and Principal Physical Features of the Site (Adapted from DOE95a)

The Yucca Mountain site is located in Nye County, Nevada approximately 150 kilometers (km) northwest of Las Vegas, Nevada (Figure 7-1). The site is at the southwestern boundaries of the Nevada Test Site and the adjoining Nellis Air Force Base and about 50 km east of Death Valley National Monument. The Yucca Mountain Region includes the southern Great Basin in southern Nevada and an adjacent area in California (Figure 7-2). The Great Basin, which is in the northern portion of the Basin and Range physiographic province, is bounded geologically by the margins of the Colorado Plateau to the east and southeast, by the Sierra Nevada and Transverse Ranges to the west and south, and by the Snake River Plain and flood basalts of the Columbia Plateau to the north. Typical Great Basin topography consists of north-south mountain ranges separating narrow structural valleys with internal drainages. The Colorado River, flowing along the margin of the Colorado Plateau and topographically isolated from Yucca Mountain, provides the only external drainage. Yucca Mountain is situated in the southern section of the Great

Basin, in the Southwest Nevada Volcanic Field (SNVF). This area is bounded on the south by the Death Valley region and the Mojave Desert of California. Yucca Mountain is a narrow ridge which trends north-south and extends approximately 20 km from the southern margin of the Timber Mountain caldera complex. The area is mapped on the following U.S. Geological Survey 7.5-minute topographic quadrangles: Amargosa Valley, Big Dune, Busted Butte, Crater Flat, East of Brady Mountain, and Pinnacles Ridge (formerly Topopah Spring NW).

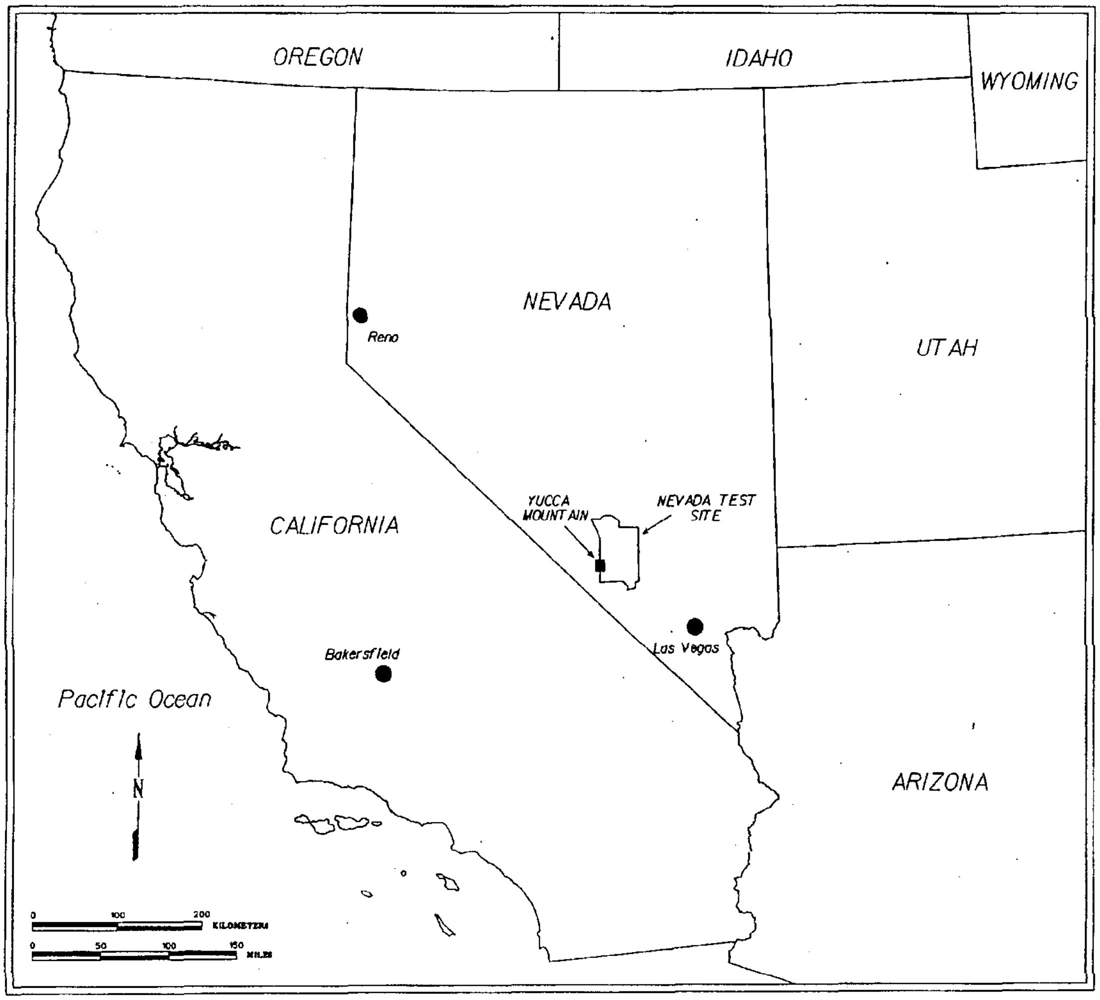

Figure 7-1. Location of Yucca Mountain (DOE94a)

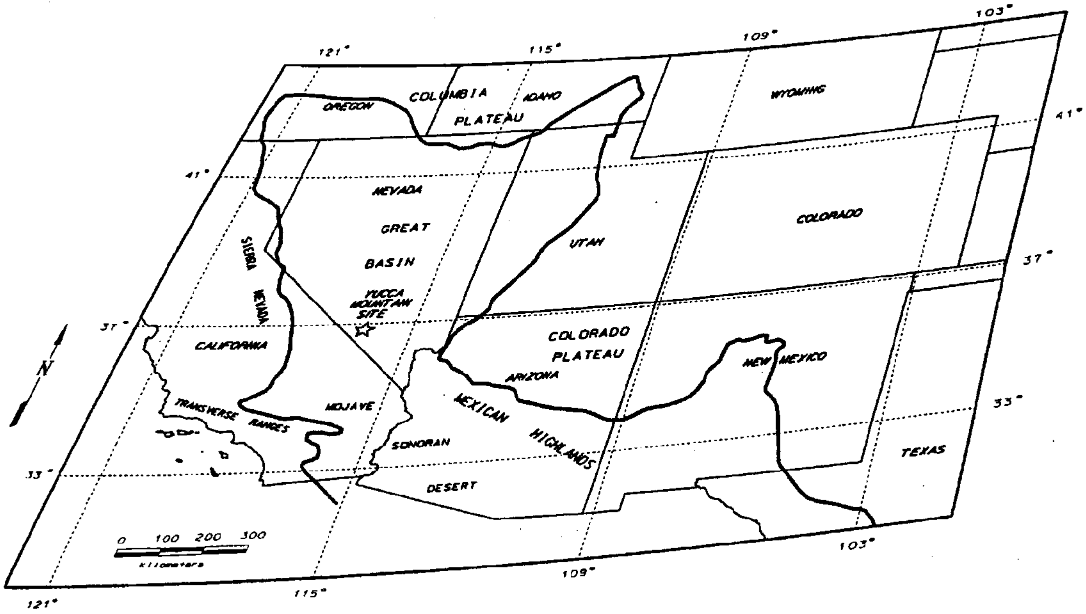

Figure 7-2. Boundaries and Larger Subdivisions of the Basin and Range Physiographic Province. Province boundary is indicated by heavy solid line (HUN74)

Yucca Mountain is an irregularly shaped upland, six to 10 km wide and about 40 km long. Uplands in the Yucca Mountain area are composed of ridge crests, valley bottoms, and intervening hill slopes (DOE88) with dominantly north-trending echelon ridges and valleys controlled by high-angled faults. The fault blocks, composed mostly of welded fine-grained volcanic rocks, are tilted eastward. As a result, the fault-bounded west-facing slopes are generally high, steep, and straight, whereas the east-facing slopes are more gentle and usually deeply dissected. Except where protected by a resistant rock layer capping the lip slopes, the ridge crests are mostly angular and eroded. Valleys range from shallow, straight, steeply sloping gullies and ravines to relatively steep, bifurcating, gently sloping valleys and canyons. Hill slopes are typically narrow and moderately steep near the crest, with progressively gentler slopes toward the valley floor. The crest elevation of Yucca Mountain ranges between 1,500 and 1,930 meters (m) above sea level. The summit is about 650 m above the floors of adjacent washes in Crater and Jackass Flats.

The main drainage system for the Yucca Mountain area, including the Timber Mountain area, the Calico Hills, and the mesas lying to the south of Timber Mountain, is in the Amargosa Valley. This drainage, east of Beatty, Nevada, carries runoff from the region south through the Tecopa basin into the southern part of Death Valley. The Amargosa Valley carries significant runoff only after extraordinarily heavy precipitation. There are no perennial streams or natural bodies of surface water on or adjacent to the Yucca Mountain. The major drainages, Solitario Canyon on the west, Forty Mile Wash on the east, and tributary drainages are primarily on the east flank of the mountain and flow only briefly immediately after rainstorms (Figure 7-3).

Bedrock exposures are common at higher elevations in the Yucca Mountain Region. Many of the hill slopes have a discontinuous veneer of blocky talus and wedges of colluvium cover the lower hill slopes. The rates of erosion in the Yucca Mountain area are lower than in similar arid areas in the southwestern U.S. and other parts of the world. Conditions contributing to these low erosion rates include existence of fine-grained volcanic rocks which are relatively erosion-resistant, insufficient runoff during interpluvial periods to remove hillslope colluvium, and topography that has not been significantly affected by Quaternary tectonic activity (WHI93). Regional erosion projections over 10,000 years are less than one meter of down cutting in canyons above the potential repository block, and less than 0.02 m of slope retreat (DOE95a).

7.1.1.2 Geologic History of the Region (Adapted from DOE95a)

The physiography and geomorphic features in the Yucca Mountain area influence the characteristics of the surface water system, and to some extent, the ground-water system as well. The flow of water into, within, and around a repository at Yucca Mountain would directly affect its ability to contain the waste over time. The composition and chemical behavior of ground water at Yucca Mountain will be affected by the type, size, and abundances of primary and secondary mineral phases in the contacting rock formations. Furthermore, the geologic processes and events important to repository performance and design can only be understood within the broader context of the geologic history of the region. Current and future geologic processes and events are a direct product of the area's geologic history; projecting their effect on repository performance requires an understanding of causes, frequencies, durations, and magnitudes over time. For example, projecting the potential frequency and magnitude of earthquakes is based on the historical record of past seismic activity. This information has been developed from records

Figure 7-3. Physiographic Features in the Yucca Mountain Site Area (DOE88)

of past seismicity and geologic studies on the effects of faulting (displacement of strata across faults, topographic features, etc.) in the vicinity of the site.

In general terms, the Yucca Mountain Region is characterized by a thick section of Precambrian and Paleozoic sedimentary rocks overlain by a sequence of Tertiary silicic volcanic rocks (see Figure 7-4). The older rocks have been folded and faulted by a compressional tectonic process and the entire stratigraphic section subsequently deformed by extensional basin-and-range tectonics. Uplifted ranges, such as Yucca Mountain, are separated by basins partially filled with alluvial deposits.

A basement complex of older Precambrian metamorphic and younger Precambrian igneous rocks is presumed to underlie the area. The basement rocks are overlain by a westward-thickening accumulation of shallow marine late Precambrian and early Cambrian marine sediments, quartzite, siltstone, shale, and carbonate rocks. These deposits are interpreted as a rifted continental margin miogeosyncline, shown in Figure 7-5, formed seaward of the highlands area. These rocks are locally fossiliferous. Deposition that continued through the Devonian Period is represented by carbonate and shale with interbedded quartzite and sandstone, thickening from up to 500 meters in western Utah to at least 6,100 meters in central Nevada.

In late Devonian and early Mississippian time, the Antler Orogeny, a mountain-building event, formed a north-northeast trending highland area adjacent to the Roberts Mountains Thrust. Large volumes of sediments eroded from the highlands into a foreland basin in the eastern half of the Great Basin, forming thick flysch[14] deposits adjacent to the highlands and shallow-water shelf carbonates to the east (Figure 7-6). Erosion of the highlands and deposition into the basin continued through the Permian Period, decreasing as the mountain-building waned. In Mesozoic and early Cenozoic time, these rocks were folded and displaced along thrust faults with extensive fracturing of the brittle rocks in the upper thrust plates. This faulting was accompanied by intrusion of granitic stocks, uplift, and erosion of the land surface (DUD90).

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[14] Flysch deposits are typified by the widespread sandstones, marls, shales, and clays exemplified by deposits occurring at the northern and southern borders of the Alps.

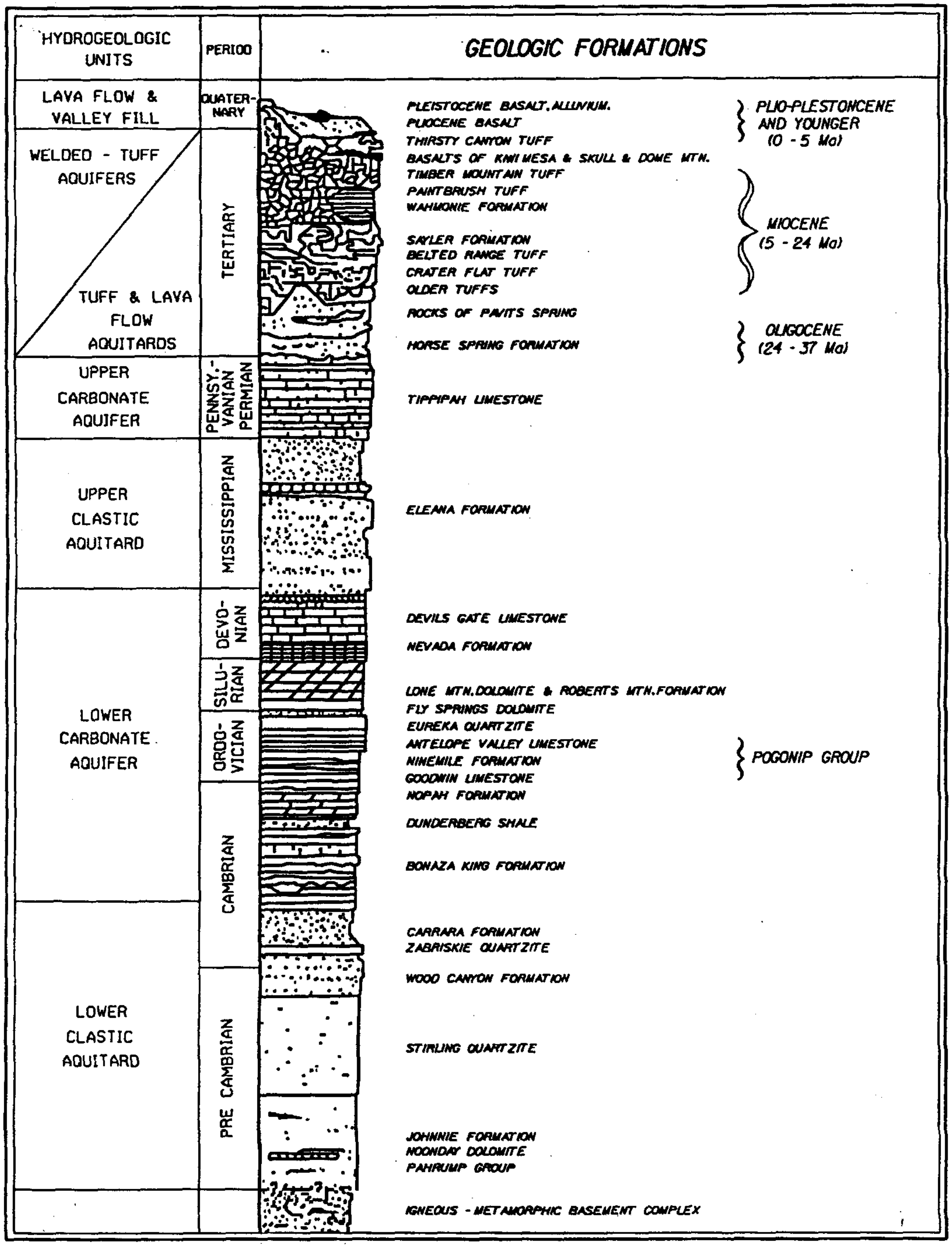

Figure 7-4. Generalized Regional Stratigraphic Column Showing Geologic Formations and Hydrological Units in the Nevada Test Site Area (Modified from DOE95a). The repository host rock at Yucca Mountain is in the Tertiary age Paint Brush Tuff.

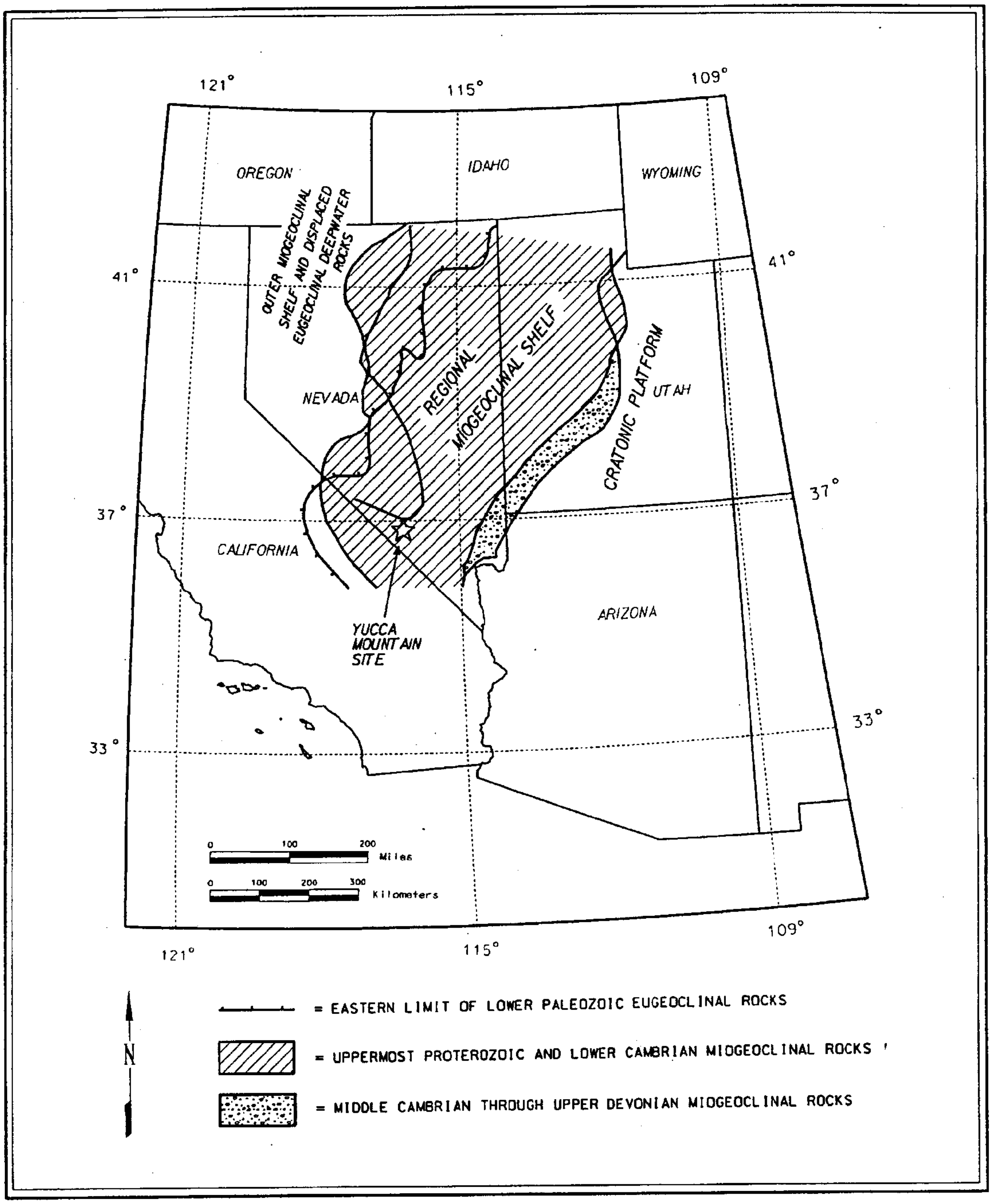

Figure 7-5. Late Precambrian Through Mid-Paleozoic Paleography of the Great Basin (Modified from DOE95a)

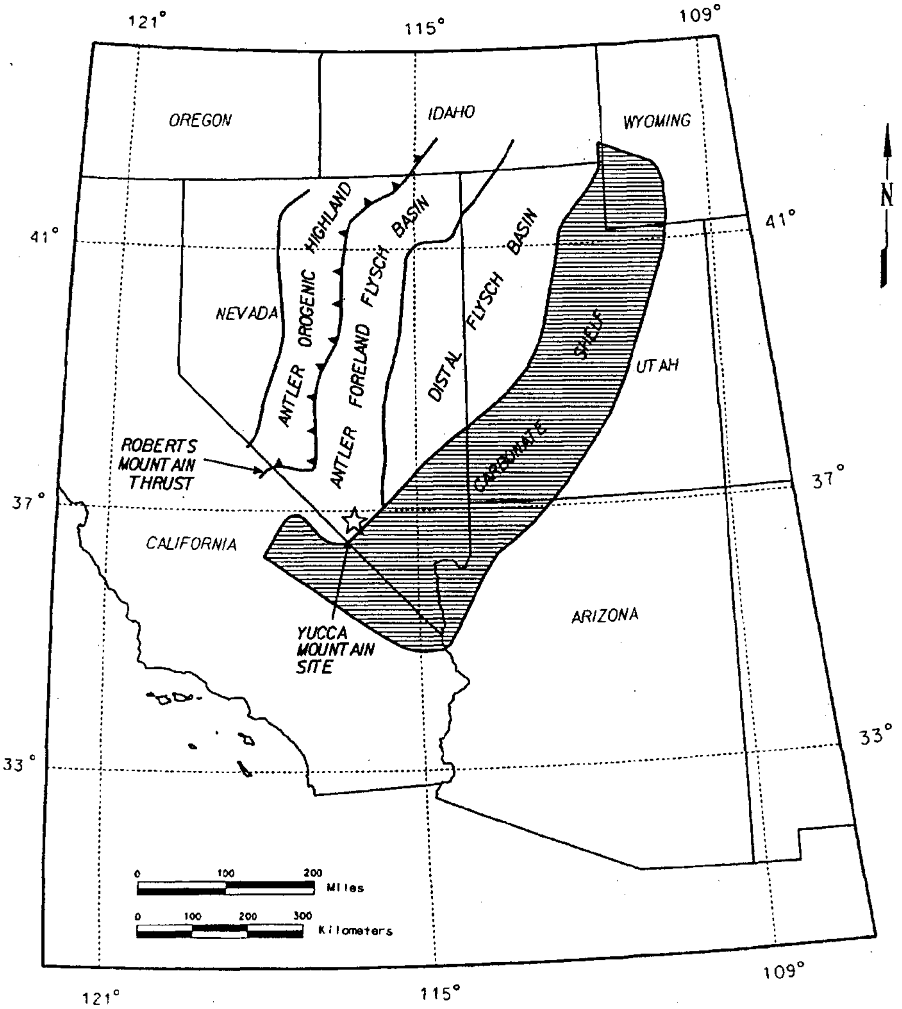

Figure 7-6. Late Devonian and Mississippian Paleogeography of the Great Basin (Modified from DOE95a)

Middle and late Cenozoic crustal uplifting and extension in the region occurred over an area 1,500 km long and 500 to 1,000 km wide. The stretching, estimated at 10 to 50 percent of the original width and locally as great as 100 percent, resulted in large north-northeast fractures with sliding and tilting of large crustal blocks, forming the characteristic structure and topography of the Great Basin.

Accompanying these crustal adjustments, volcanic eruptions in the vicinity of Yucca Mountain formed a series of calderas and deposited numerous thick beds of pyroclastics, tuff, and lava, aggregating up to three km in thickness near Yucca Mountain. The major episodes of silicic volcanism ceased about 7.5 million years ago (mega annum; Ma); however, smaller basaltic eruptive centers formed in the basins adjacent to Yucca Mountain perhaps as recently as 4,000 years ago.

7.1.1.3 Stratigraphy of the Yucca Mountain Area (Adapted from DOE95a)

An understanding of the stratigraphy of the rocks at Yucca Mountain and the surrounding area is important to: 1) designing and constructing the repository, 2) assessing the potential of the natural barrier to retard the movement of radionuclides from the repository, and 3) describing the expected behavior of ground water movement through these rocks. For example, the physical properties of the rocks at the repository horizon determine the effects of heat generated by the radioactive waste on the near-field environment in the postclosure time period. They can also determine the speed at which radionuclides can be transported through the repository.

The stratigraphy of the southern Great Basin is highly varied, with formations ranging in age from Precambrian to Holocene, that is, from 500 million to less than 400,000 years. These rocks, briefly described in Table 7-1, are divided into eight general groups based on age, lithology, and history.

At Yucca Mountain, the stratigraphy is dominated by mid-Tertiary rocks of volcanic origin that erupted from the southwestern Nevada volcanic field. The stratigraphic sequence can be divided into four general categories based on similarities in lithology, age, and history of deposition or emplacement: 1) pre-Cenozoic rocks, 2) mid-Tertiary pyroclastic rocks, 3) younger basalt, and 4) late Tertiary to late Quaternary surficial deposits (Figure 7-7). These categories are discussed in the following sections.

Table 7-1. Stratigraphy of the Southern Great Basin

Older Precambrian Crystalline Rocks	These include extensive exposures of older Precambrian schist and gneiss and younger Precambrian igneous rocks in eastern Clark and southeastern Lincoln Counties. Outcrops of Precambrian granite, pegmatite, amphibolite, and gneiss exist in southern Lincoln County. Schist, gneiss, and gneissic quartz monzonite, possibly as young as late Proterozoic, are exposed in the Bullfrog Hills and Trapman Hills of southern Nye County.
Precambrian and Lower Cambrian Rocks	Late Precambrian and early Cambrian strata include a westward-thickening prism of quartzite, siltstone, shale, and carbonate interpreted as a rifted continental margin miogeosyncline. This prism has been divided into two depositional systems in Nevada: an eastern quartzite and siltstone system and a western siltstone, carbonate, and quartzite province.
Middle Cambrian through Devonian	Middle Cambrian through Devonian rocks exposed in the southern Great Basin consist of carbonates and shales, with interbedded quartzite and sandstone with thicknesses from up to 500 m in western Utah to at least 6,100 m in central Nevada. Strata of middle Cambrian through Devonian age comprise the Lower Carbonate Aquifer.
Mississippian through Permian Sedimentary Rocks	Thick flysch* deposits result from erosion of the north-northeast trending highland formed during the Antler Orogeny in late Devonian and early Mississippian time. This sedimentation continued through Permian time, declining as the orogeny waned.
Mesozoic Rocks	Mesozoic sedimentary rocks, locally present only in Clark County, consist of continental and marine sandstone, siltstone, and limestone of the Triassic and Jurassic Aztec Sandstone, Chinle Formation, and Moenkopi Formation. Approximately 30 separate Mesozoic to Tertiary granitic plutons are exposed in Esmeralda County, west of Yucca Mountain. These range in size from less than one km^2 to the 1,000 km^2 Inyo Batholith.
Tertiary Sedimentary Rocks	Tertiary sedimentary rocks, such as the Esmeralda and Horse Spring Formations, crop out throughout the southern Great Basin. These consist of poorly to moderately consolidated alluvial deposits and fresh water limestones in variable thicknesses of up to 1,000 m. They are commonly found interbedded with volcanic deposits.
Tertiary and Quaternary Igneous Rocks	The most prevalent Tertiary igneous rocks of the southern Great Basin are pyroclastic deposits of rhyolitic to trachytic composition. Eruptions from four calderas at Yucca Mountain between approximately seven and 16 Ma produced a complex mixture of pyroclastic flow and fall deposits, epiclastic deposits, and subsidiary lavas approximately 3050 m in thickness at Yucca Mountain. This was followed by scattered, small-volume basaltic or bimodal basaltic-andesitic lava and scoria eruptions.
Tertiary and Quaternary Surficial Deposits	Late Tertiary to Quaternary surficial deposits occur throughout the region as unconsolidated alluvial fan, pediment, and basin fill deposits of highly variable thickness and character.

* Deposits largely of sandy and calcareous shales.

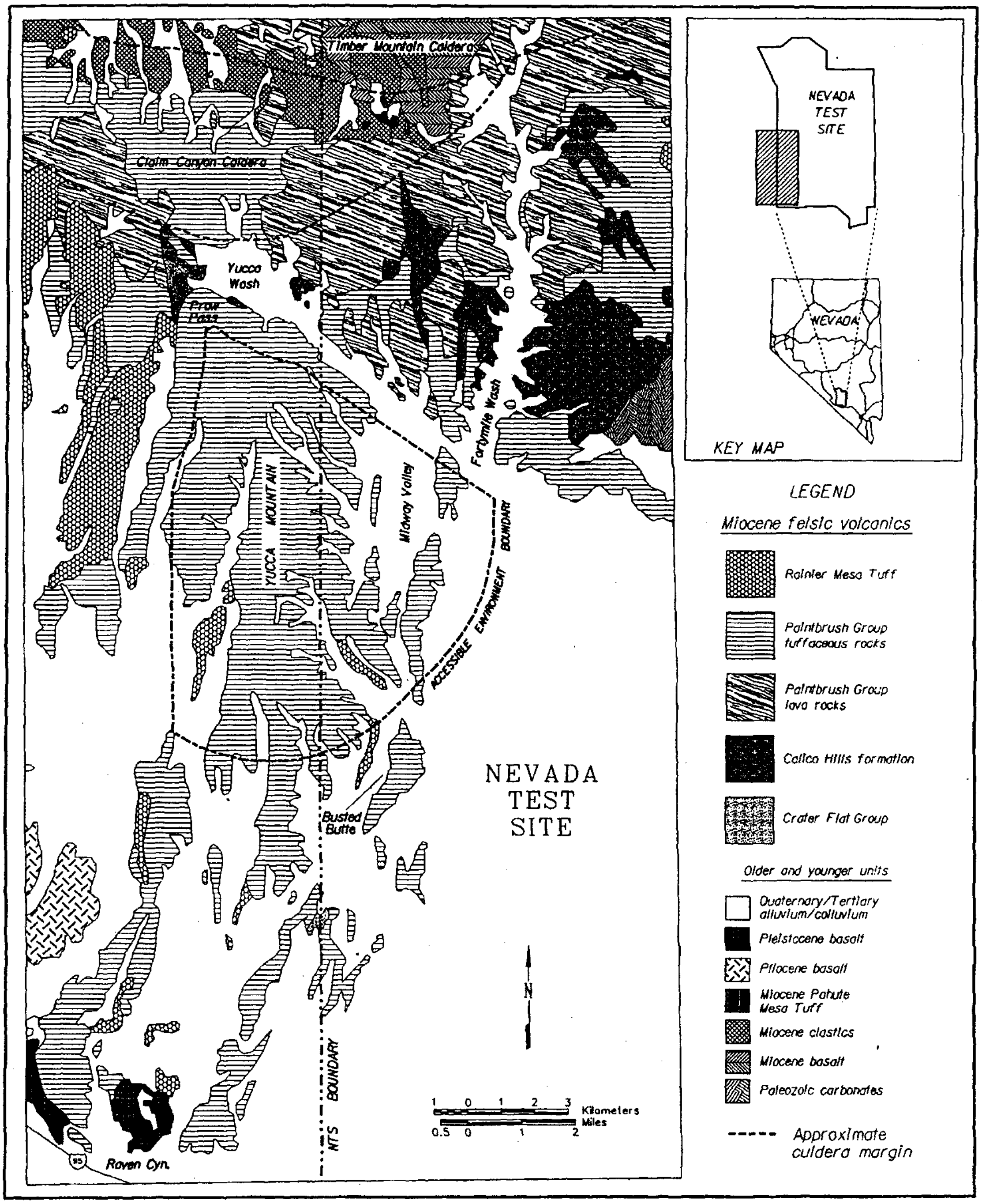

Figure 7-7. Simplified Geologic Map Showing the Distribution of Major Lithostratigraphic Units in the Yucca Mountain Area (Modified from DOE95a).

Pre-Cenozoic Rocks

Pre-Cenozoic rocks, believed to consist primarily of Paleozoic sedimentary strata, underlie the volcanic rocks at Yucca Mountain. Little detailed information is available as to their thickness, lithology, and contact with overlying stratigraphic units. Exposures of highly deformed Paleozoic rocks occur at scattered localities in the vicinity of Yucca Mountain, including the Calico Hills to the east, Bare Mountain to the west, and Striped Hill to the south. Carbonate rocks have been detected at a depth of 1,244-1,807 m in a borehole two km east of Yucca Mountain (DOE95a).

In the Calico Hills, exposures of carbonate rocks occur in the upper plate of a gently dipping thrust fault over a black shale sequence containing minor amounts of siltstone, sandstone, conglomerate, and limestone. These strata are locally highly folded, making correlation with stratigraphic units elsewhere in the region uncertain.

At Bare Mountain, there is a varied sequence of pre-Cenozoic sedimentary and meta-sedimentary rocks, totaling about 6,650 m in thickness and ranging from Precambrian to Mississippian in age. Fourteen Paleozoic and two Proterozoic formations are represented. Dolomite and limestone dominate, with minor stratigraphic units of clastic rocks (quartzite, sandstone, and siltstone).

Paleozoic rocks found at a depth of 1,244 to 1,807 m in a borehole two km east of Yucca Mountain are almost entirely dolomites and have been identified as related to the Lone Mountain Dolomite and the Roberts Mountains Formation. Seismic reflection data are inconclusive as to the thickness and extent of pre-Cenozoic rocks underlying Yucca Mountain, but the thickness is believed to be substantial.

Mid-Tertiary Pyroclastic Rocks

These rocks, resting unconformably on older pre-Cenozoic rocks, compose the portion of Yucca Mountain most important to the design and performance of the repository because they are the host rocks for the repository and define the pathways for ground-water flow into and out of the repository. Volcanic rocks ranging in age from about 11.4 to 15.2 Ma form the bulk of the volcanic sequence, including the host rock of the potential repository, known as the Topopah Spring tuff (Figure 7-8). The volcanic sequence consists of welded and nonwelded silicic pyroclastic flow, fallout tephra deposits, and volcanic breccias erupted from nearby calderas in the southwestern Nevada volcanic field. Non-welded tuffs typically have large primary porosity.

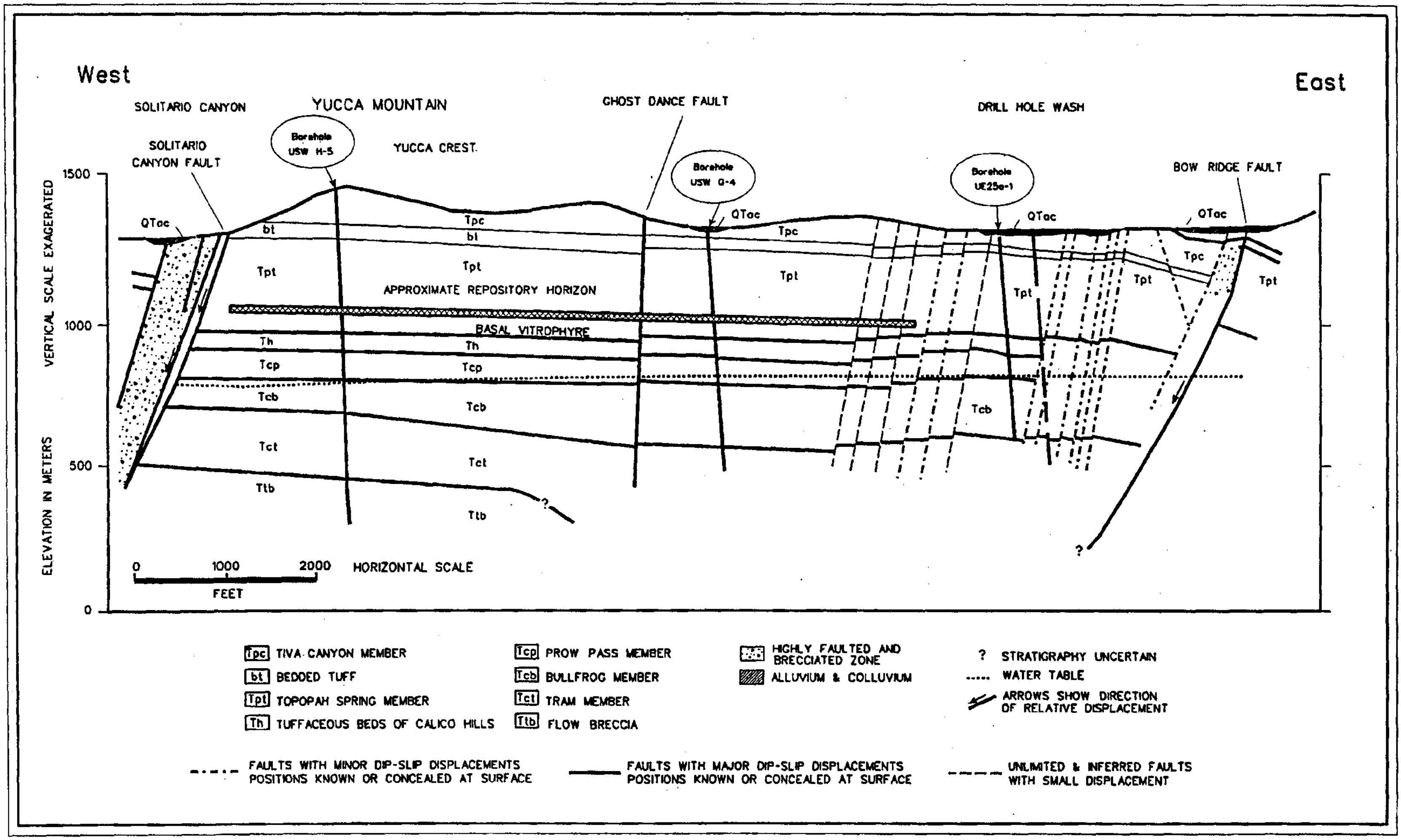

Figure 7-8. East-West Geologic Cross Section for the Yucca Mountain Site. (This figure shows the relative positions of various rock units at the site, including the unit proposed for the potential repository (Topopah Spring Member of the Paintbrush Tuffs) and the fault zones that are closest to the site (USG88a))

However, the large porosity is poorly interconnected resulting in low permeability. The harder, welded tuffs are commonly more highly fractured and, consequently, have significant bulk permeability. The principal stratigraphic units are listed in Table 7-2, in order of increasing age (adapted from DOE94a).

Table 7-2. Principal Stratigraphic Units

Unit	Age (Ma)
Younger Post-caldera Basalts	0.27-3.8[a]
Older Post-caldera Basalts	8.5-10.5[a]
Shoshone Rhyolite Lava	9
Timber Mountain Group	
Ammonia Tanks Tuff	11.45
Rainier Mesa Tuff	11.6
Post-Tiva/pre-Ranier Rhyolites	12.5
Paintbrush Group	
Tiva Canyon Tuff	12.7
Yucca Mountain Tuff	-
Pah Canyon Tuff	-
Topopah Spring Tuff	12.8
Calico Hills Formation	12.9
Crater Flat Group	
Prow Pass Tuff	13.1
Bullfrog Tuff	13.25
Tram Tuff	13.45
Dacite Lava and Flow Breccia	
Lithic Ridge Tuff	14.0
Older Tuffs - Pre-Lithic Ridge	14-16

(a) Based on information from DOE95a to be discussed subsequently in Section 7.1.1.7. The age of the older post-caldera basalts ranges from 10.4 to 6.3 Ma; for the younger post-caldera basalts, the age ranges from 4.9 to 0.004 Ma.

Many of these formations, particularly those in the Prow Pass Tuff, Calico Hills Formation, and the Paintbrush Group, are further subdivided into members or units. The formations are summarized below, from oldest to youngest, with an emphasis on thickness, general composition and minerals important to radionuclide retardation along potential ground water transport pathways.

a. Pre-Lithic Ridge Volcanics. The oldest known volcanic rocks in the area were deposited approximately 15 million years ago and are represented in site boreholes by 45 to 350 m of bedded tuffaceous deposits, pyroclastic flow deposits, and quartz-latitic to rhyolitic lavas and flow breccia. Correlation of these rocks with other rocks in the area is difficult because of their heterogeneous character and varying degrees of alteration.

b. Lithic Ridge Tuff. This thick, massive pyroclastic flow deposit overlying the older tuffs appears to represent several eruptive surges and ranges in thickness from 185 m north of the site to 304 m at the south end of the site. This unit is nonwelded to moderately welded and has been extensively altered to smectites and zeolites.

c. Dacitic Lava and Flow Breccia. Dacitic lava and flow breccia overlie the Lithic Ridge Tuff in deep boreholes at the northern and western parts of Yucca Mountain but are absent elsewhere. Observed thicknesses in boreholes range from 22 m to 249 m. Much of the unit has been moderately to intensely altered to smectite clays and zeolites.

d. Crater Flat Group. This group, overlying dacitic lavas and flow breccias in the northern part of Yucca Mountain and the Lithic Ridge Tuff in the southern part, includes three rhyolitic, ash-flow-tuff sheets—the Tram, Bullfrog, and Prow Pass Tuffs, in ascending order. The Crater Flat Group is distinguished from other pyroclastic units at Yucca Mountain by the relative abundance of quartz and biotite phenocrysts.

- **Tram Tuff**. The Tram Tuff appears to comprise at least 28 separate magmatic pulses and includes two subunits distinguished on the basis of the relative abundance of lithic fragments. The lower subunit is rich in these fragments throughout, while the upper unit is poor in lithic clasts. The upper subunit, 126 to 171 m thick, is partially welded and has a microcrystalline ground mass.

  There are six to 22 m of ash-fall and reworked tuff, primarily comprising zeolitic pumice clasts, between the Tram and the overlying Bullfrog Tuff.

- **Bullfrog Tuff**. The Bullfrog Tuff is 68 to 187 m thick, consisting mostly of pyroclastic flow deposits with thin-bedded tuffaceous deposits. North of borehole USW G-4 (see Figure 7-8), this tuff consists of a moderately to densely welded core enclosed by nonwelded to partially welded zones. To the south, the tuff is composed of two welded zones separated by a one-meter-thick bed of welded fallout tephra.

- **Prow Pass Tuff**. The Prow Pass Tuff is a sequence of variably welded pyroclastic deposits that erupted from an unidentified source between 13.0 and 13.2 Ma. The formation, 90 to 165 m thick across the repository area, consists of four pyroclastic units overlying a variable sequence of bedded tuffs. These units, designated Unit 1 through 4 by decreasing age, are characterized by orthopyroxene pseudomorphs and the abundance of siltstone and mudstone lithic clasts. Unit contacts are defined by fallout tephra horizons and abrupt changes in sizes and amounts of pumice and lithic clasts.

A bedded tuff unit at the base of the Prow Pass Tuff consists of unwelded, altered tuffaceous deposits with a total thickness ranging from less than one meter to 11 m in boreholes.

Unit 1, a pumiceous pyroclastic flow deposit with an aggregate thickness of 25 to 70 m in cored boreholes, consists of three subunits separated on the basis of their lithic clast content.

Unit 2 consists of nonwelded to partially welded lithic-rich pyroclastic flow deposits with an aggregate thickness of three meters to 34 m in cored sections. The unit has not been subdivided since distinguishing characteristics are lacking; however, locally preserved ash horizons and abrupt changes in the amount and size of pumice and lithic clasts suggest at least three flow deposits.

Unit 3 consists of 40 m to nearly 80 m of multiple welded pyroclastic flow deposits, either separated by thin fallout tephra horizons or defined by abrupt changes in the amount and size of pumice and lithic clasts. Two of three flow deposits have been identified in most core holes but have not been correlated.

Unit 4 is distinguished by comparatively abundant pseudomorphic pyroxene in pumice clasts and rock matrix and by a comparatively low ratio of flesic to mafic phenocryst minerals. This unit includes three irregularly distributed subunits. The aggregate thickness in cored sections ranges from about 4 m to as much as 20.5 m.

e. Calico Hills Formation. The Calico Hills Formation, a series of rhyolite tuffs and lavas, includes five pyroclastic units overlying a bedded tuff unit and a local basal sandstone unit in the Yucca Mountain area. The formation thins southward across the site area, declining from about 290 m in the north to 43 m in the south. Basal beds of the Calico Hills Formation include two units. One unit consists of a nine- to 39-meter-thick bedded tuff unit containing coarse-grained fallout, primary and reworked pyroclastic-flow deposits, and fallout-tephra deposits. The other unit consists of a 0- to 5.5-meter-thick volcaniclastic sandstone unit with abundant lithic clasts and swarms of altered (to clay minerals) pumice clasts, interbedded with rare pyroclastic-flow deposits.

The pyroclastic units are composed of one or more pyroclastic-flow deposits separated by pumice- and lithic-fallout tephra deposits included with the unit lying above. Five units, designated Units 1 through 5 by decreasing age, can be distinguished on the basis of textural characteristics (percentages of various clastic material). In the northern part of Yucca Mountain (below the proposed repository horizon) the formation is high in zeolites, which compose 60 to 80 percent of the rock. In the southern portion of Yucca Mountain, the rock remains vitric.

Unit 1 is a nonwelded, lithic rich, pyroclastic-flow deposit ranging from 0 to 58 m thick in cored sections. Pumice clasts constitute 10 to 15 percent of the unit and lithic clasts increase from three to seven percent at the top to 15 to 20 percent at the base; phenocrysts compose seven to 12 percent of the rock.

Unit 2, 0 to 54 m thick, is a nonwelded, pumiceous, pyroclastic-flow deposit composed of 20 to 40 percent pumice clasts and up to five percent lithic clasts. Fallout deposits at the base are ash-rich, have a porcelaneous appearance, and are less than one meter thick.

Unit 3 is a nonwelded lithic-rich pyroclastic flow deposit 22 m to 100 m thick in cored sections. The unit is generally composed of 10 to 40 percent pumice clasts and five to 10 percent lithic clasts.

Unit 4 is a 0 to 57 m thick nonwelded, pumiceous pyroclastic flow deposit, with pumice clasts and lithic clasts constituting 10 to 30 percent and one to five percent, respectively. Thinly bedded ash-fall deposits, reworked pyroclastic-flow tuffs, and tuffaceous sandstone form a thin basal subunit.

Unit 5 is a nonwelded to partially-welded pyroclastic-flow deposit ranging from 0 to 20 m thick in cored sections. The unit is characterized by a bimodal distribution of pumice clast sizes—larger, slightly flattened clasts of 20 to 60 mm and smaller equidimensional clasts of two to 12 mm. The unit is composed of 20 to 30 percent pumice clasts and two to five percent lithic clasts.

f. Paintbrush Group. This group—one of the most widespread and voluminous caldera-related assemblages in the southwestern Nevada volcanic field—consists of primary pyroclastic flow and fallout tephra deposits, lava flows, and secondary volcaniclastic deposits from eolian and fluvial processes.

Eruptive centers for the Topopah Spring and Pah Canyon Tuffs are uncertain, but the Claim Canyon caldera (see Figure 7-7) is identified as the source of the Tiva Canyon and perhaps the Yucca Mountain Tuffs.

- The **Topopah Spring Tuff** (Figure 7-8) is the host rock for the proposed Yucca Mountain repository. The tuff has a maximum thickness of about 350 m in the vicinity of Yucca Mountain. The unit is divided into two members—an upper crystal-rich member and a lower crystal-poor member—each of which is subdivided based on variations in crystal content, phenocryst assemblage, pumice composition, distribution of welding and crystallization zones, depositional features, and fracture characteristics.

  The upper, crystal-rich member is characterized by greater than 10 percent phenocrysts, with a basal transition zone where the percentage increases from five to 10 percent. The member is divided into vitric, nonlithophysal, and local lithophysal zones.

The lower, crystal-poor member is characterized by less than three percent phenocrysts and is divided into devitrified rocks of the upper lithophysal, middle nonlithophysal, and lower lithophysal zones and a vitric zone. Below the vitric zone (the vitrophyre), concentrations of clay and zeolites increase significantly from alteration of the volcanic glass.

- The **Pah Canyon Tuff**, a simple cooling unit composed of multiple flow units, reaches its maximum thickness of 70 m in the northern part of Yucca Mountain and thins southward. This tuff varies from nonwelded to moderately-welded. Throughout much of the area, vitric pumice clasts are preserved in a sintered or lithified nondeformed matrix.

- The **Yucca Mountain Tuff**, a simple cooling unit in the Yucca Mountain area, varies in thickness from 0 to 30 m. Generally nonwelded, the unit is nonlithophysal throughout Yucca Mountain but contains lithophysae where densely welded in northern Crater Flat.

- The **Tiva Canyon Tuff** (Figure 7-8) is a large-volume, regionally extensive, compositionally-zoned (from rhyolite to quartz latite) tuff sequence that forms most of the exposed surface rocks exposed at Yucca Mountain. The tuff ranges in thickness from 100 to 150 m. Separation into crystal-rich and crystal-poor members and into zones within these members is based on similar criteria and characteristics discussed above for the Topopah Spring Tuff.

g. <u>Post-Tiva Canyon, pre-Rainier Mesa Tuffs</u>. A sequence of pyroclastic flow and fallout tephra deposits occurs between the Tiva Canyon Tuff and the Rainier Mesa Tuff in the vicinity of Yucca Mountain. The sequence ranges from 0 to 61 m thick and is intermediate in composition between Tiva Canyon and Rainier Mesa Tuffs.

h. <u>Timber Mountain Group</u>. This group includes all of the quartz-bearing pyroclastic flow and fallout tephra deposits that erupted from the Timber Mountain caldera complex about 11.5 Ma (see Figure 7-7). The complex consists of two overlapping, resurgent calderas—one formed by eruption of the Rainier Mesa Tuff and a younger, nested one formed by eruption of the Ammonia Tanks Tuff.

- The **Rainier Mesa Tuff** is one of the most widespread pyroclastic units of the Yucca Mountain area. It is a compositionally-zoned unit consisting of high-silica rhyolite tuff overlain by a considerably thinner quartz latite tuff restricted to the vicinity of the Timber Mountain caldera. Exposed thicknesses along the west side of the caldera are as great as 500 m. The formation is absent across much of Yucca Mountain, but appears in down-thrown blocks of large faults in valleys on either side. The tuff is nonwelded at the base, grading upward into partially- to moderately- welded devitrified tuff.

- The **Ammonia Tanks Tuff** consists of welded to nonwelded rhyolite tuff with a highly variable thickness of up to 215 m. It is absent across Yucca Mountain, but is exposed in the southern part of Crater Flat.

Hydrostratigraphy

The formal geologic stratigraphy for those rocks near the repository horizon has been reorganized into four major hydrostratigraphic units for ground-water modeling and performance assessment. The groupings are based primarily on the degree of welding of the tuffs. These units and their relationship to formal geologic stratigraphy are as follows (descriptions taken from DOE95b):

- Tiva Canyon welded (TCw) unit: Consists of the moderately- to densely-welded zones of the Tiva Canyon geologic member. This unit is characterized by low matrix porosity (~10 percent), low matrix saturated hydraulic conductivity (~10^{-11}m/s), and high fracture density (10-20 fractures/m^3).

- Paintbrush nonwelded (PTn) unit: Consists of the lower partially-welded to nonwelded zones of the Tiva Canyon geologic member, partially-welded to nonwelded Yucca Mountain and Pah Canyon members, the porous interlayers of bedded tuffs, and the upper partially-welded to nonwelded part of the Topopah Spring member. This unit is characterized by high matrix porosity (~40 percent), high matrix saturated hydraulic conductivity (~10^{-7} m/s), and low fracture density (~1 fracture/m^3).

- Topopah Springs welded (TSw) unit: Consists of the welded zones of the Topopah Spring member. This unit is characterized by low matrix porosity (~10 percent), low matrix saturated hydraulic conductivity (~10^{-7} m/s), and high fracture density (8-40 fractures/m^3). The basal vitrophyre of the Topopah Spring member (TSv) is generally identified as a subunit because of its lower porosity as compared to the TSw unit.

- Calico Hills nonwelded (CHn) unit: consisting of the moderately-welded to nonwelded zones of the Topopah Spring member underlying the basal vitrophyre, the partially-welded to nonwelded tuffs of the Calico Hills formation, and other partially-welded to nonwelded tuffs located below the Calico Hills formation (i.e., the Prow Pass, Bullfrog and Tram members of the Crater Flat Unit). Portions of the lower Topopah Spring member are vitrified and zeolitic alteration appears in both the lower part of the Topopah Spring member and in the tuffaceous beds of the Calico Hills. This leads to a further division of this unit into vitric (CHnv) and zeolitic (CHnz) subunits. The fracture density (2-3 fractures/m^3) is similar in both zones, and the porosity in the vitric tuffs (~30 percent) is marginally higher than that of the zeolitic tuffs. However, matrix saturated hydraulic conductivity of the CHnv subunit (~10^{-9} m/s) is roughly two orders of magnitude higher than that of the CHnz subunit.

In some discussions of Yucca Mountain stratigraphy, the stratigraphic column is divided into thermal/mechanical units, rather than the more formal geologic formations or the hydrostratigraphic units (see, for example, Figure 6-7 in DOE94a). The boundaries between the thermal/mechanical units tend to be defined by the interface between welded and non-welded lithologies and the units are very similar to the hydrostratigraphic groupings.

Younger Basalt

The youngest volcanic rocks in the Yucca Mountain area are the basalts at Lathrop Wells, where multiple eruptions occurred over a period of about 120,000 years with the latest event occurring less than 10,000 years ago.

Surficial Deposits

Surficial deposits in the area reflect the effects of erosive processes and affect the surficial recharge of water to the underlying rocks. Numerous Quaternary/Tertiary surficial deposits have been defined in the Yucca Mountain area. These include alluvial, colluvial, and eolian deposits. The alluvial deposits range in age from late Tertiary (probably late Miocene) to late Holocene and generally consist of sandy gravel (granules to boulders), often with interbedded sands. These deposits occur along the washes, drainage channels, and valley slopes. The colluvial deposits are primarily of Quaternary age and generally consist of a thin mantle of angular gravels on slopes and highlands.

Two deposits of eolian sand ramp are defined, both formed of massive to poorly-bedded sand with five to 50 percent fine angular gravel. One deposit (late and middle Pleistocene) forms partially-dissected aprons between gullies on lower hill slopes. The other deposit (Holocene and late Pleistocene) forms undissected and poorly-exposed sand ramps along Forty Mile Wash.

Summary

The most important rocks affecting the design and performance of the proposed Yucca Mountain repository are the sequence of Miocene volcanic rocks that overlie, underlie, and are the host rocks for the repository. These silicic rocks consist of ash-fall and air-fall tuffs produced by eruptions from the Timber Mountain-Oasis Valley caldera complex. Most of the exposed surface rock over the repository is the 100-150 m thick Tiva Canyon Tuff. Below this, is the Yucca Mountain Tuff, which is largely nonwelded and up to 30 m thick. The Claim Canyon caldera segment lying to the east of the proposed repository site is a possible source for rocks in these units. The repository horizon is in the Topopah Spring Tuff which has a maximum thickness of 350 m in the vicinity of Yucca Mountain. These units are all part of the Paintbrush Group.

Next, in descending sequence, is the Calico Hills Formation consisting of rhyolite tuffs and lavas which, in turn, is underlain by the Prow Pass Tuff in the Crater Flat Group. The Prow Pass Tuff is 90 to 165 m thick under the potential repository location. The surface of the water table lies near the base of this unit. Lower lying units, generally in the saturated zone, include the 68 to 187 m thick Bullfrog Tuff and the Tram Tuff. These two tuffs are separated by six to 22 m of ash-fall and reworked tuff comprised mainly of zeolitic pumice clasts.

7.1.1.4 Major Fault Features of the Yucca Mountain Area (Adapted from DOE95a)

The faults present in the site area are important for several reasons. To avoid adverse effects of fault movement, areas of active fault movement should be avoided when deciding on the location of surface waste handling facilities for the repository, as well as when designing the underground waste emplacements locations. The fractured rocks in fault zones can also act as preferential pathways for ground-water movement and radionuclide migration. Their location and hydrologic properties are important for developing an understanding of the flow system and performing quantitative calculations of ground-water movement essential to assessing the repository's performance.

Faulting and the Structural Setting Around Yucca Mountain

The location of faults, and the extent of recent movement along these faults, is important to the location and design of surface facilities and the layout of the underground repository at the Yucca Mountain site. Seismic conditions in the area show at least some degree of correlation with the faults observed. Seismic activity could affect surface facilities of the repository. In addition, the fractured rock zones typical of fault zones often serve as preferential pathways for the movement of ground water. Rapid flow of ground water along fractures in the site area has been observed and DOE's current layout of the repository has been designed to avoid emplacing wastes in areas where the host rock is prominently fractured (e.g., the Ghost Dance Fault zone).

Yucca Mountain consists of a series of north-trending, eastwardly tilted structural blocks that were segmented by west-dipping, high-angle normal faults during a period of major extensional deformation. The site is situated near the southern end of the northwest trending Walker Lane Belt, a zone of northwest-directed shear about 700 km long and 100 to 300 km wide. This Belt absorbs part of the transform motion of the regional plates and the strain from the extension of the Great Basin. It parallels the San Andreas fault and the Sierra Nevada Mountains and is truncated on the south by the east-west Garlock fault (Figure 7-9).

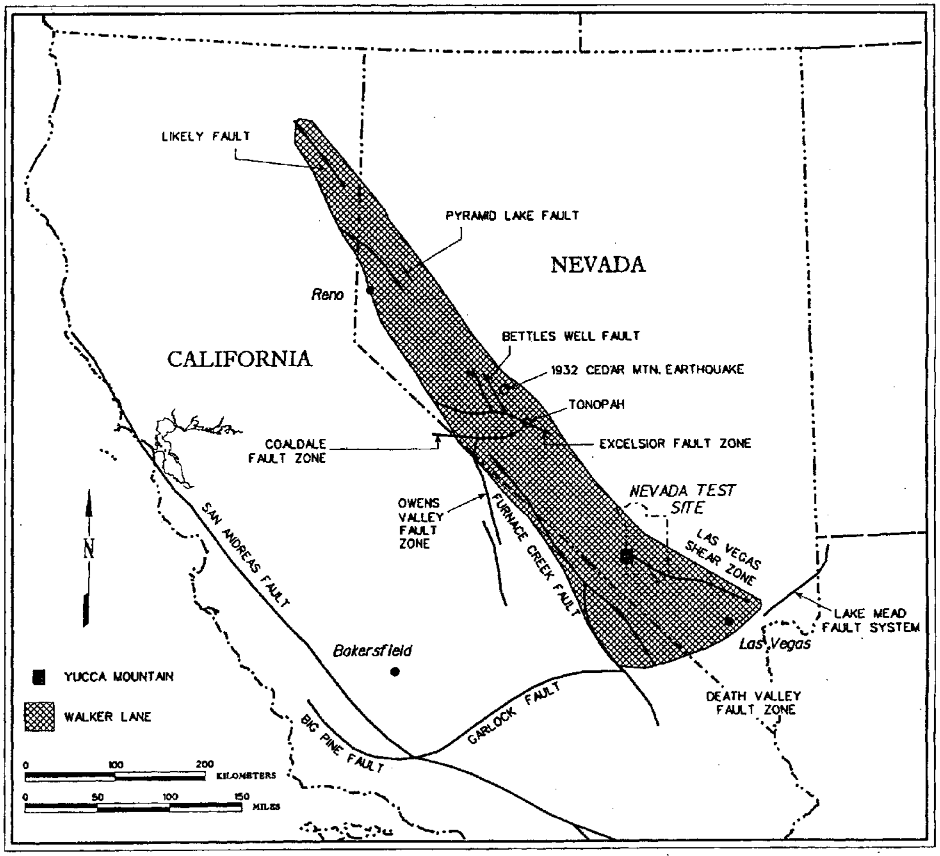

Figure 7-9. The Walker Lane Belt and Major Associated Faults (DOE88)

Cenozoic deformation probably took place on preexisting structures and is characterized by strike-slip faulting, regional folding, and large-scale extension (see, for example, STE90). The current type of deformation in the Walker Lane Belt probably began about five million years ago as an overlap between the right-lateral shear caused by the North American and Pacific plates and the gravity-driven extension of the regional uplift in the Great Basin. In the modern stress field, northwest-striking faults move with left-lateral strike-slip or oblique-slip along the fault planes.

In the Walker Lane Belt, right angle-shear totaling 4.27 to 7.35 millimeters per year (mm/yr) is distributed along three major faults: the Owens Valley, Panamint Valley-Hunter Mountain, and Death Valley-Furnace Creek faults. This, along with lesser amounts of slip on other fault systems to the east, correlates well with the approximate 10 mm/yr of slip estimated from field measurements.

The major north-trending faults transecting or close to Yucca Mountain are, from west to east, the Crater Flat, Windy Wash, Fatigue Wash, Solitario Canyon, Stagecoach Road, Ghost Dance, Bow Ridge, Midway Valley, and Paintbrush Canyon faults (Figure 7-10). Bedrock has been displaced downward and to the west along these faults, which show predominantly dip slip, with varying amounts of left-oblique slip, along the faults. Estimates of bedrock displacement over the past 12 million years range from less than 100 m to as much as 600 m, with the displacement increasing southward along each fault. The faults are projected up to 25 kilometers, but surface exposures can usually be traced only one kilometer or less. Dips of the fault planes are generally 70 to 75 degrees.

Several northwest-trending faults have been identified along valleys, the most prominent being the Yucca Wash, Sever Wash, Pagany Wash, and Drill Hole Wash faults. A northwest-trending shear zone, the Sundance Fault, crosses the potential repository site (Figure 7-11). These faults are thought to be strike-slip faults, with nearly horizontal slickenside lineations and vertical displacements generally less than five to 10 m.

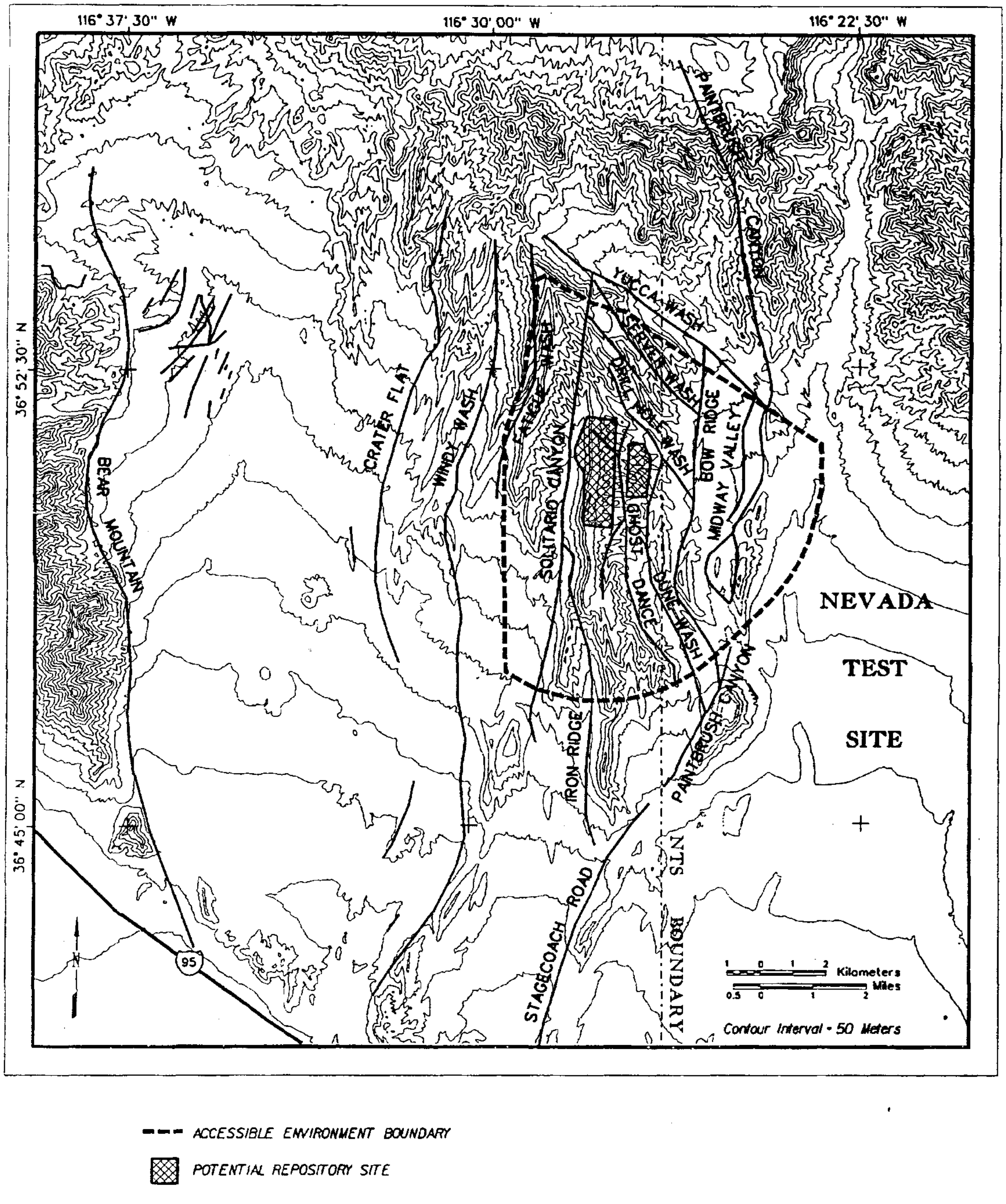

Figure 7-10. Major North-Trending Faults in the Vicinity of Yucca Mountain (DOE95k)

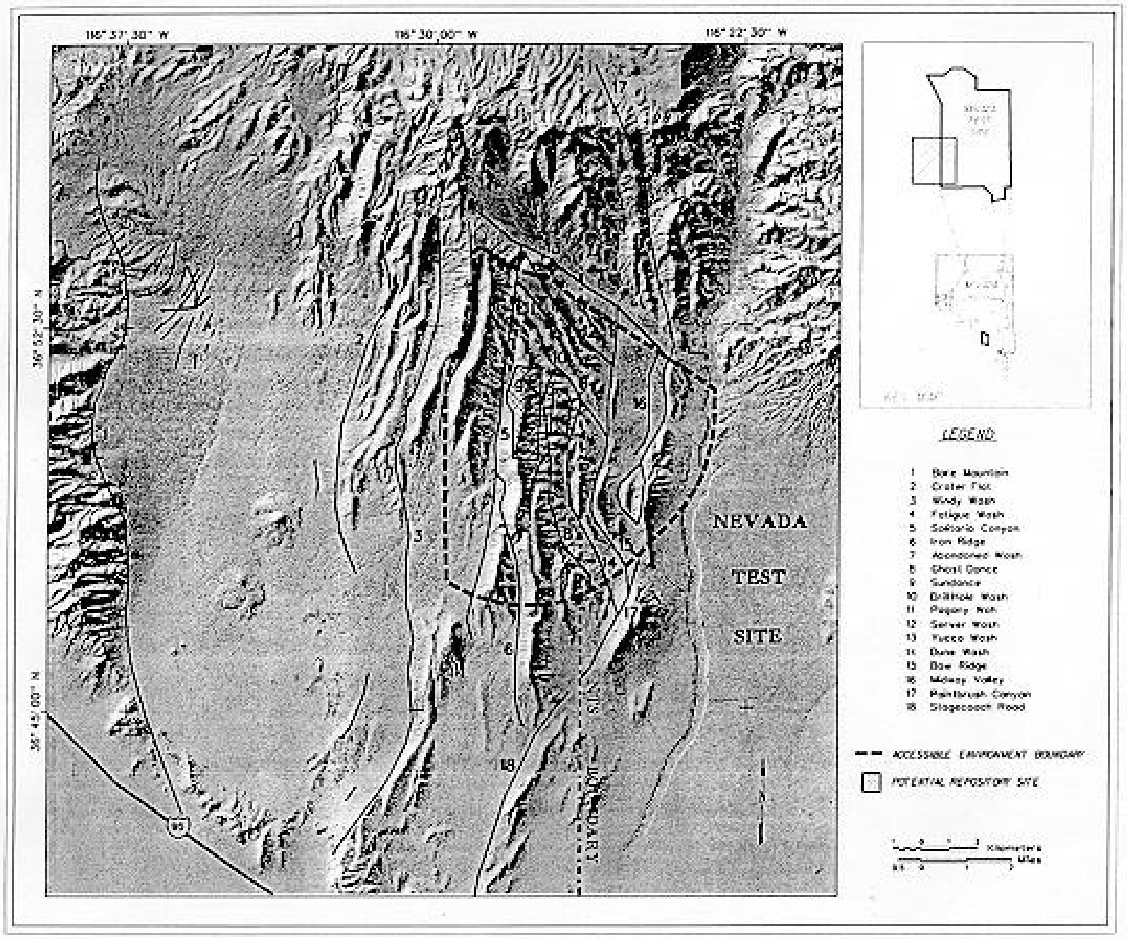

Figure 7-11. Index Map of Faults at and near Yucca Mountain (Modified from DOE95k)

Quaternary Faulting in the Yucca Mountain Area

Of particular concern for the Yucca Mountain site are faults considered to be Type I faults, as classified by the U.S. Nuclear Regulatory Commission (NRC). Type I faults or fault zones are those subject to displacement and are sufficiently long or located such that they may affect repository design and/or performance. Evidence of movement during the Quaternary Period (the past 1.6 million years) is the primary criterion for identification of these faults

Studies to identify and characterize faults that may be of concern to the Yucca Mountain facility have focused on evaluating the potential Type I faults within 100 km of the site, as well as a few major faults at greater distances. Some 82 known or suspected Quaternary faults and fault rupture combinations have been identified within 100 km of the Yucca Mountain site (Figure 7-12). DOE reports that 38 of these are capable of generating a peak acceleration of 0.1 g (the force of gravity) or greater at the ground surface of the proposed repository site; these are classified as relevant earthquake sources.[15] An updated compilation of faults has been prepared by the U.S. Geological Survey (USGS) which identifies 67 faults with demonstrable or questionable evidence of Quaternary movement and the capability of accelerations of at least 0.1 g at an 84 percent confidence limit (WHI96). Significant known or suspected Quaternary faults located within 20 km of the Yucca Mountain site are briefly described in Table 7-3.[16] The more distant major fault zones include: the Garlock Fault (125 kilometers south), the Owens Valley Fault (140 kilometers west), the Stewart-Monte Cristo Valley Fault (200 kilometers northwest), and the Dixie Valley Fault (see page 3.1-8 *et seq*, DOE95a).

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[15] The NRC-supported program of the Center for Nuclear Waste Regulatory Analyses has identified 52 Type I faults within a 100-km radius of Yucca Mountain (NRC97a).

[16] NRC-supported studies have identified 24 Type I faults within a 10-km radius of Yucca Mountain capable of generating peak accelerations of greater than 0.3 g (NRC97a).

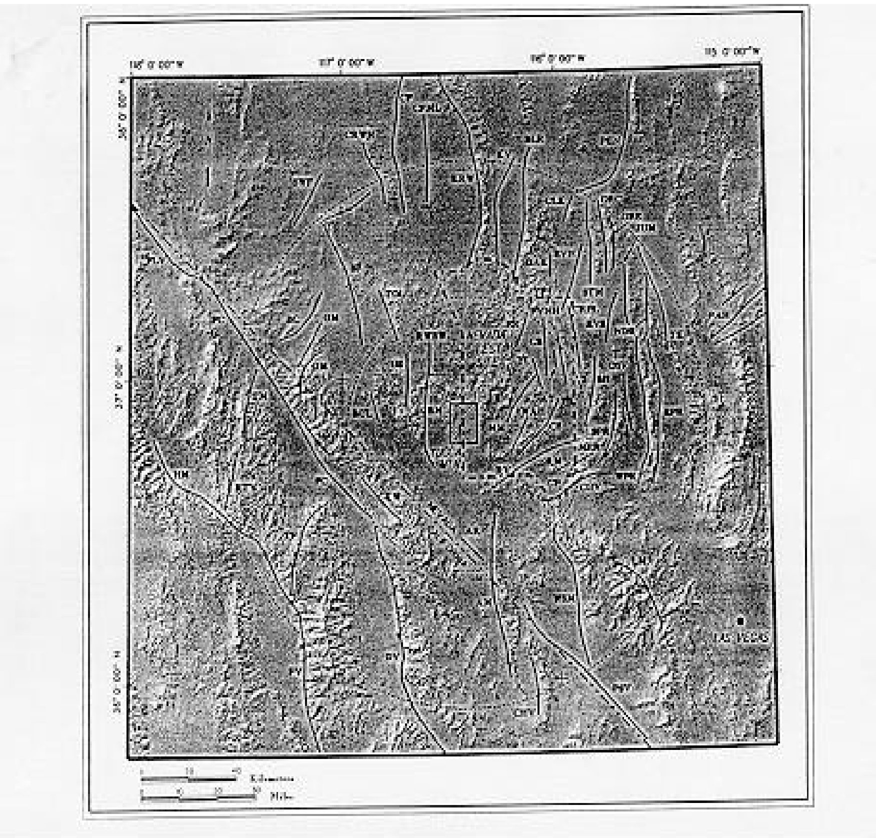

Figure 7-12. Index Map of Known or Suspected Quaternary Faults in the Yucca Mountain Region (Modified from DOE95a). Circles are 50 and 100 km radii from Yucca Mountain (YM). Faults are identified as follows:

AM - Ash Meadow
AR - Amargosa River
AT - Area Three
BC - Bonnie Claire
BH - Buried Hills
BLR - Belted Range
BM - Bare Mountain
BUL - Bullfrog Hills
CB - Carpetbag
CF - Cactus Flat
CFML - Cactus Flat-Mellan
CGV - Crossgrain Valley
CHV - Chicago Valley
CLK - Chalk Mountain
CP - Checkpoint Pass
CRPL - Cockeyed Ridge-Papoose Lake
CRWH - Cactus Range-Wellington Hills
CS - Cane Spring
DV - Death Valley
EPR - East Pintwater Range
ER - Eleana Range
EVN - Emigrant Valley North
EVS - Emigrant Valley South
FC - Furnace Creek
FLV - Fish Lake Valley
GM - Grapevine Mountains
GRC - Groom Range Central
GRE - Groom Range East
GV - Grapevine
HM - Hunter Mountain
ISV - Indian Springs Valley
JUM - Jumbled Hills
KRW - Kawich Range West
KV - Kawich Valley
KW - Keane Wonder
LM - La Madre
MER - Mercury Ridge
MM - Mine Mountain
NDR - North Desert Range
OAK - Oak Spring Butte
OSV - Oasis Valley
PAH - Pahranagat
PEN - Penoyer
PM - Pahute Mesa
PSV - Pahrump-Stewart Valley
PV - Panamint Valley
PVNH - Plutonium Valley-North -Halfpint Range
RM - Ranger Mountains
RTV - Racetrack Valley
RV - Rock Valley
RWBW - Rocket Wash-Beatty Wash
SF - Sarcobatus Flat
SOU - South Ridge
SPR - Spotted Range
STM - Stumble
SWF - Stonewall Flat
SWM - Stonewall Mountain
TK - Tikaboo Valley
TM - Tin Mountain
TOL - Tolecha Peak
TP - Towne Pass
WAH - Wahmonie
WPR - West Pintwater Range
WSM - West Springs Mountain
YF - Yucca Flat
YL - Yucca Lake

Table 7-3. Known or Suspected Quaternary Faults within 20 km of the Proposed Repository Site

Fault Name	Trend	Apparent Length	Dip	Distance from Site	Latest Activity
Bare Mountain	N	20 km	E50-70	15 km W	Most recent surface rupture 16 to 21 thousand years ago (ka); one to 1.5 m displacement; recurrence interval 100 ka; slip rate 0.01 mm/yr
Crater Flat	NE	14-20 km	W70	5 km W	Quaternary deposits (17 to 30 ka) displaced less than one m
Windy Wash	N-NE	25 km	W63	3 km W	At least four events in past 300 ka; recurrence interval 75 ka; Pleistocene displacement approximately one m
Fatigue Wash	N	17 km	W73	2 km W	Five late Quaternary events; cumulative displacement 2.2 m
Solitario Canyon	N	20 km	W72	at W boundary	Multiple mid- to late-Quaternary events; 1.7 to 2.5 m displacement of Quaternary deposits
Stagecoach Road	N-NE	10 km	W73	SE corner of area	Three to seven events during late Quaternary; displacement one to 2.3 m; recurrence interval five to 70 ka; slip rate 0.01 to 0.06 mm/yr
Ghost Dance	N	3.5km	W80-90	center of area	No offset or fracturing of late Pleistocene or Holocene noted except for a single fracture in one trench. Fracture zone varies up to 213 m across.
Dune Wash	N-NW	8 km	W	at E side	No evidence of Quaternary activity found
Bow Ridge	N	10-19km	W65-75	2 km E	Most recent event 48±20 ka; cumulative displacement 0.3 to 0.7 m; likely recurrence interval 60 to 100 ka; slip rate 0.002 to 0.01 mm/yr
Midway Valley	N	1-4 km	W	3 km E	No recognizable ruptures of Quaternary deposits
Paintbrush Canyon	N	25-32 km	W41-71	E side of Yucca Mtn.	Six to eight events evident; Midway Valley excavation: most recent event at 38±6 ka; cumulative displacement 1.7 to 2.7 m; recurrence interval 20 to 80 ka, slip rate 0.007 to 0.02 mm/yr; Busted Butte exposure: Quaternary displacement 4.8 to 7.8 m; recurrence interval 40 to 125 ka; slip rate 0.006 to 0.01 mm/yr

Several of the north-trending faults show evidence of activity during Quaternary time; the total displacements on the most active of these is estimated to be less than 50 meters over the past 1.6 million years. Since the late Quaternary Period (<128,000 years), displacements have been as much as six m but are more commonly in the one to 2.5 m range. Recurrence intervals on the faults showing movement in the Quaternary Period fall in the range of tens of thousands of years, commonly between 30-80 thousand years with slip rates typically in the range of 0.01-0.02 mm/yr. The northwest-trending faults do not appear to have been active.

The three major faults in the immediate region of Yucca Mountain are the Ghost Dance fault, which passes through Yucca Mountain and the proposed repository; the Bow Ridge fault, just to the east of Yucca Mountain; and the Solitario Canyon fault, just to the west of Yucca Mountain. According to DOE's interpretation of available data, the Solitario Canyon fault has shown no significant movement over the last 40,000 to 110,000 years. No movement has occurred during the last 10,000 years. The most recent surface-rupturing motion on the Bow Ridge fault is estimated to have occurred 48,000 ±20,000 years ago, with a recurrence interval most likely in the range of 60,000 to 100,000 years. There has been no offset or fracture on the Ghost Dance fault for the past 20,000 years.

7.1.1.5 Tectonics and Seismicity (Adapted from DOE95a)

The fault systems and the seismic history of the Yucca Mountain area must be considered in the larger context of regional tectonics. By so doing, predictions of future seismic hazards and their potential effects on the repository, as well as the performance of natural barriers, can be made with reasonable certainty, within the limits of the available data. This section discusses what is currently known about the tectonic setting of the region encompassing the repository site. Data concerning the seismicity of the area and historic earthquake activity are also presented.

Regional Plate Tectonic Setting

The plate tectonic setting of the southwestern United States is dominated by the interaction of the North American and Pacific Plates. In the Yucca Mountain Region, particularly west of Yucca Mountain, this interaction is complicated by the overlap of right-lateral plate boundary stress from these plate movements and extensional stress from the Basin and Range tectonics.

Based on geologic and geodetic measurements, the Pacific plate appears to be moving northwest at approximately 50 mm/yr relative to the North Atlantic plate. The stresses generated from this movement are distributed to structural features on the North American Plate and contribute to the tectonic processes (extension or compression of the crust, folding and faulting, etc.) in the region. About 35 mm/yr of the motion from the Pacific Plate is absorbed by the San Andreas fault system; another 5 mm/yr may be absorbed by coastal strike-slip faults parallel to and west of the San Andreas fault. The eastern edge of the Sierra Nevada microplate (composed of the Sierra Nevada Mountains and the Great Valley of California) appears to move northwest at approximately 10 mm/yr. This latter movement, between the eastern edge of the Sierra Nevada Mountains and the western edge of the Colorado Plateau, is most likely to contribute to the seismicity and tectonic processes around the Yucca Mountain site (Figure 7-13). Uncertainties in the understanding of the regional tectonic processes include: the amount of compression normal to the San Andreas fault induced by Pacific plate motion (N36°W ±2°), the rate of relative motion between plates, and the amount of motion taken up within the Sierra Nevada microplate.

The timing and mechanisms for producing the crustal extension which characterizes the structural and physiographic features of the Great Basin are a subject of debate. Several mechanisms have been proposed for the extensional tectonic processes that produced the major land forms of the Great Basin. Relatively high-angle, planar, normal faults cutting brittle crust can accommodate up to 10 or 15 percent of the crustal extension. Normal faults at a high angle at the surface and curving to lower angles at depth (listric faults) may accommodate much greater extension. Modeling of very low angle detachment faults suggests extensive crustal thinning that may accommodate extension of the crust by 200 percent or more.

The typical Basin and Range structures were developed by about 11 Ma. They are tilted fault block ranges with relatively large displacement, high-angle normal faults exposed at the surface bounding one or both sides of each range. Scott (SCO90) suggests that rates of fault movement were highest between 13 - 11.5 Ma and thereafter decreasing over time.

This crustal extension varied across the region in time and space. One thought is that rapid Miocene extension migrated westward from Yucca Mountain after about 11.5 Ma and may also have been nonuniform from north to south. Pliocene and later extension, accompanying a postulated region-wide uplift starting about five million years ago, is more evenly distributed and is taken up by movement on high-angle normal faults at depth which are coincident with the Miocene faults expressed at the surface. This belief is consistent with the evidence of the existence of faulting to depths of 15 km or more indicated by the pattern of hypocenters for the current seismicity in the region.

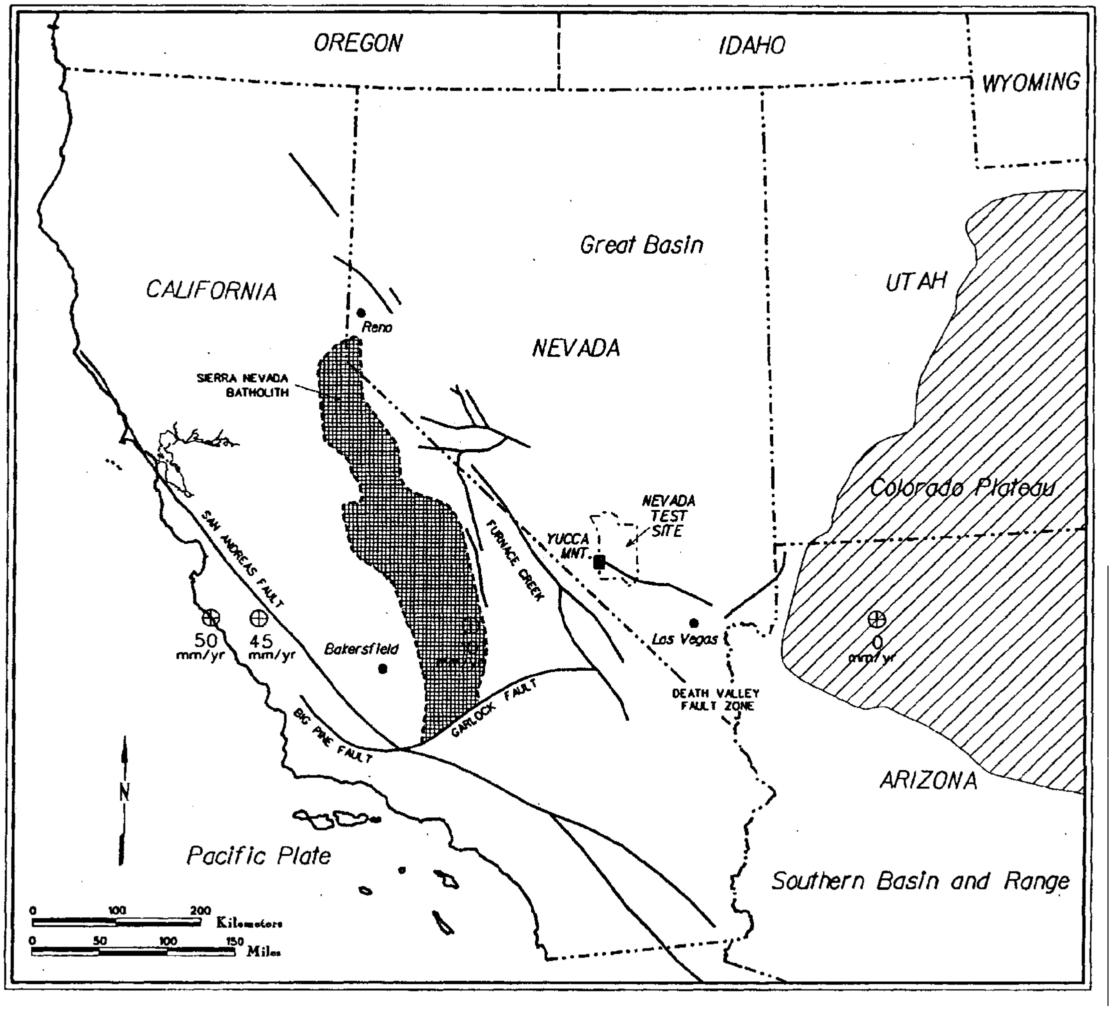

Figure 7-13. Sketch Map of the Western United States Showing Some Major Structural Features. Symbols (⊕) at the latitude of Las Vegas give approximate motions toward the NW in mm/yr relative to a "stable North America." This interpretation suggests that 10 mm/yr of NW movement occurs between the Colorado Plateau and the crest of the Sierra Nevada Range, 35 mm/yr occurs on the San Andreas Fault, and five mm/yr occurs west of the San Andreas Fault. This is consistent with the paleoseismic data and historic observations of strike slip faulting in this region. (Modified from DOE95a)

Structural Features and Seismicity

The relationship between specific structural features, particularly faults, and seismicity in the Basin and Range Province is not entirely clear. The Central Nevada Seismic Belt (CNSB), for example, is clearly associated with major faults or fault systems showing historic surface rupture. However, other zones of seismic activity and areas of diffuse activity show no evidence of historic surface faulting. One example is the east-west seismic belt, which includes the Nevada Test Site.

The apparently poor correlation between earthquakes and faults may be attributable, at least in part, to several factors: 1) the short historical record relative to the long recurrence intervals for earthquakes, 2) the difficulty of accurately locating epicenters in this remote area, and 3) the unknown geometry of faults at depth. Study of the paleoseismic record for the Quaternary Period suggests that, in the Yucca Mountain Region, recurrence intervals for surface rupture are on the order of thousands to tens of thousands of years.

Seismology of the Yucca Mountain Area

In the region around the site, there are several zones in which seismicity is concentrated: the Sierra Nevada-Great Basin Boundary Zone (SNGBZ), the CNSB, the Southern Nevada Transverse Zone (SNTZ), the Garlock Fault, and the Mojave Block. All of the zones, except the Mojave Block, are wholly or partially in the Walker Lane Belt, a major tectonic element of southwestern Nevada. In addition, there is a broad distribution of seismic activity that is not associated with any known major tectonic feature throughout much of the Great Basin.

The **Walker Lane Belt** tectonic element (Figure 7-9) consists of nine structural blocks acting more or less independently. The belt is defined by a style of faulting within and bounding the blocks which ranges from northwest-trending right-lateral slip (the Pyramid Lake, Walker Lane, and Inyo-Mono blocks) to northeast-trending left-lateral slip (the Carson, Spotted Range-Mine Mountain, and Lake Mead blocks) to east-west trending left-lateral slip (Excelsior-Coaldale block). Cumulative lateral offset on individual major faults ranges from a few kilometers up to 100 kilometers and faults rarely extend to adjacent blocks.

The Walker Lane Belt probably developed in the Mesozoic Period and is still active. Most of the faults show evidence of Cenozoic movement and numerous zones exhibit Quaternary and Holocene offset (STE90). Although the recurrence interval for the late Quaternary faulting is generally thousands to tens of thousands of years, recurrence may be on the order of decades in some sections of the seismic zone, e.g., the CNSB.

Of the four seismic zones identified in the Walker Lane Belt, the SNTZ is nearest to the Yucca Mountain site and is the most significant to repository performance. Although the other zones exhibit recent seismic activity, they are further removed from the Yucca Mountain site and are less likely to affect the repository.

The **Southern Nevada Transverse Zone**, which includes Yucca Mountain, is an arcuate belt of seismicity about 150 kilometers wide, extending from the southern region of the Intermountain Seismic Belt (in southwestern Utah) to the Mammoth Lakes area in California. Historic earthquakes in this zone have been of moderate magnitude with no documented surface rupture. Earthquake events include the 1902 Pine Valley, Utah (M_L 6.3)[17], the 1966 Caliente-Clover Mountain, Nevada (M_L 6.0), and the 1992 Little Skull Mountain, Nevada (M_L 5.6) near the proposed site (see Table 7-3).

Seismic Distribution

Studies of the large Great Basin earthquakes suggest faulting on steeply dipping fault planes that penetrate the upper 15 kilometers of crust as the focal mechanism for many of the earthquakes observed. In general, mainshock hypocenters for earthquakes of magnitude seven or greater in this region can be located on the down-dip projection of the surface rupture observed along faults identified in the field, suggesting that large Great Basin events occur on steeply dipping planar faults at depths less than about 15 kilometers.

Three—with perhaps two additional possible—seismic gaps (areas of no recent seismic activity) have been identified in the western Great Basin. These gaps occur between the rupture zones of major historic earthquakes and contain structures that show evidence of prehistoric activity. Seismic gaps are generally considered to be significant in plate-boundary regions but their relevance for interplate regions such as the Great Basin is not clear. These gaps may represent areas of prolonged low or no seismic activity or areas where stresses are not being released by fault movements.

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[17] M_L is a measurement of the magnitude of the seismic event. See Table 7-4 for a definition of this and other magnitude measures.

Table 7-4. Significant Earthquakes within 320 km of Yucca Mountain Site Since 1850

Owens Valley, CA, 1872	March 26, 1872; estimated at M_w 7.8 to M_s 8.0[*a]; considered largest historic event of the Basin and Range; surface ruptures along 90 to 110 km on Owens Valley fault; average net oblique slip of 6.1 ±2.1 m and up to four m vertical displacement; liquefaction of unconsolidated sediments.
Wonder, NV, 1903	Fall 1903; estimated magnitude 6.5; rupture of the Gold King fault; ruptures of five to 16 km with fissures up to 1.5 m wide and 1.5 m deep in alluvium; in the same area as the 1954 Fairview Peak-Dixie Valley earthquakes.
Cedar Mountain, NV, 1932	December 21, 1932; M_s 7.2; about 61 km of discontinuous faulting in a belt six to 14 km wide; displacements up to 1.8 m horizontal and 0.5 m vertical; analysis indicated main shock was two sources occurring about 20 seconds apart; an M_w 6.7 event and a second M_w 6.6 event; series of seven moderate events in this part of the CNSB from 1932 to 1939.
Excelsior Mountains, NV, 1934	January 30, 1934; M_L 6.3 (M_w 6.1); on Excelsior-Coaldale section of the Walker Lane belt; about 60 km west-southwest of the 1932 event; foreshock of M_L 5.6 preceded mainshock by 45 min.; surface rupture 1.4 km in length and less than 13 cm vertical displacement. An M_L 5.5 earthquake occurred on August 9, 1943, approximately 40 km southeast.
Rainbow Mtn.-Stillwater, NV, 1954	July 6, 1954; two events of M 6.6 and M 6.4 in Rainbow Mountain area were followed on August 24 by the Stillwater M 6.8 event initiating a six-year period of 10 events greater than M 5.5 in the CNSB.
Fairview Peak-Dixie Valley, NV, 1954	December 16, 1954; an M_L 7.3 event on the Fairview fault followed four minutes later by an M_L 6.9 event rupturing the Dixie Valley fault; diffuse fracture zone covering an area 100 km by 30 km from Mount Anna to the northern part of Dixie Valley; displacements four m right lateral and three m vertical on Fairview Peak fault and over two m vertical in Dixie Valley.
Caliente-Clover Valley, NV, 1966	On August 16, 1966; M_L 6.0; near Caliente, Nevada, about 210 km east-northeast of Yucca Mountain. The source depth is estimated at 6 km; with the focal mechanism a strike-slip motion on steeply dipping plates oriented either north-northeast or west-northwest.
Mammoth Lakes, CA, 1978-1980	An M_L 5.8 earthquake midway between Bishop and Mammoth Lake in October, 1978, was followed 18 months later (May, 1980) by a swarm-like sequence of four events (M_L 6.5, M_L 6.0, M_L 6.7, M_L 6.3) within two days. This sequence was accompanied by inflation of the resurgent dome in the Long Valley caldera. Activity continued with moderate earthquake swarms in the southern part of the caldera with spasmodic tremor sequences usually associated with magma injection at depth. The Chalfant sequence, discussed below, occurred to the east in 1986.

Table 7-4. Significant Earthquakes within 320 km of Yucca Mountain Site Since 1850 (Continued)

Chalfant Valley, CA, 1986	On July 21, 1986, an M_L 6.6 earthquake occurred in the Chalfant Valley in eastern California about 15 km north of Bishop with about 10 km of rupture along the White Mountains fault zone. The source-depth was located 11 km below the surface and the focal mechanism indicates right lateral slip on a plane oriented north-northwest dipping 70° southwest.
Landers, CA, 1992	The Landers sequence began April 23rd with the M_L 6.2 Joshua Tree earthquake, followed by a sequence of 6000 events. On June 28, 1992, an M_s 7.6 earthquake near Landers, California, ruptured sections of several mapped north- to northwest-trending faults and several concealed unmapped north-trending faults in the south-central portion of the Mojave block. An extensive aftershock sequence followed, extending 85 km north of the mainshock and 40 km to the south. The sequence included the M_s 6.7 Big Bear earthquake three hours after and 30 km west of the mainshock. Surface rupture extended for 85 km, with displacement averaging two to three meters across the rupture zone, up to 6.7 m on the Emerson fault, and minor rupture of faults within 30 km of either side of the main rupture zone. The Lander event was followed by a sudden increase in seismic activity in the western U.S. up to 1250 km from the mainshock, with an intense cluster of events in the Walker Lane belt. This included the M_L 5.6 Little Skull Mountain earthquake on June 29, 1992, approximately 20 km SE of Yucca Mountain.
Eureka Valley, CA, 1993	On May 17, 1993, an M_L 6.1 earthquake occurred 30 km southeast of Bishop, California. The hypocenter was located nine kilometers below the surface in the southern part of Eureka Valley. Preliminary analysis indicates normal faulting on a northeast striking plane, perhaps paralleling a north-northwest trending inferred Quaternary fault in the area.

[*a] Terms used for earthquake magnitude in the table above include:

M_L	Local magnitude; this is the original Richter scale, developed in California for earthquakes with epicentral distances less than 600 km and focal depths less than 15 km; uses waves with periods of about 1 s; saturates at $M = 7.25$;
M_s	Surface-wave magnitude; suitable for global distance; uses waves with 20 s periods; saturates at about $M = 8.6$;
M_w	Moment magnitude; based on seismic moment ($M_0 = \mu AD$), where μ = shear modulus, A = area of fault rupture, and D = fault displacement; $M_w = 2/3 \log M_0 - 10.7$; does not saturate;
M	This is assumed to be local magnitude.

Significant Historical Earthquakes

Figure 7-14 depicts the epicenters for earthquakes of magnitude 3 and greater occurring within 320 kilometers of the proposed site from 1850 through 1992. These data show a clustering of seismicity in the CNSB and the SNGBZ, as well as in the southern Mojave Desert and along the San Andreas fault zone. In addition to those identified in the figure, numerous small magnitude earthquakes have occurred in clusters or as isolated events throughout much of Nevada. The Garlock Fault and a large portion of the southern Great Basin appear to show relatively little seismic activity during this period.

Earthquakes occurring since 1850 within 320 km of the Yucca Mountain site with magnitudes greater than 6 are summarized in Table 7-3. These either resulted in surface rupturing or represent the largest event in a particular seismic-source zone. The most recent strong earthquake (M_L =5 or greater) in the vicinity of Yucca Mountain was the Little Skull Mountain (M_L = 5.6) event in June 1992, associated with the Landers, California earthquake earlier that year.

Studies of ground motion from recorded seismic activity around Yucca Mountain and of surface features susceptible to ground motion effects, suggests that Yucca Mountain has not been subject to ground accelerations at the surface in excess of 0.2 g for over several tens of thousands of years. At the depth at which waste is likely to be emplaced in the repository, the effects of ground motion would be expected to be significantly less. These ground accelerations do not present excessive demands on seismic facility design requirements for the repository or its associated surface facilities.

The largest seismic event in the immediate area of Yucca Mountain since 1978 was an M_L 2.1 event on November 18, 1988, centered 12 km northwest of the proposed repository location. An earthquake of magnitude M_W 5.7 occurred on June 29, 1992, beneath Little Skull Mountain approximately 20 km southeast of Yucca Mountain. This earthquake is the largest ever recorded (in about 100 years of records) in the vicinity of the site. It caused minor structural damage to the Yucca Mountain project field office near Yucca Mountain but had no apparent effect on geologic features near the mountain.

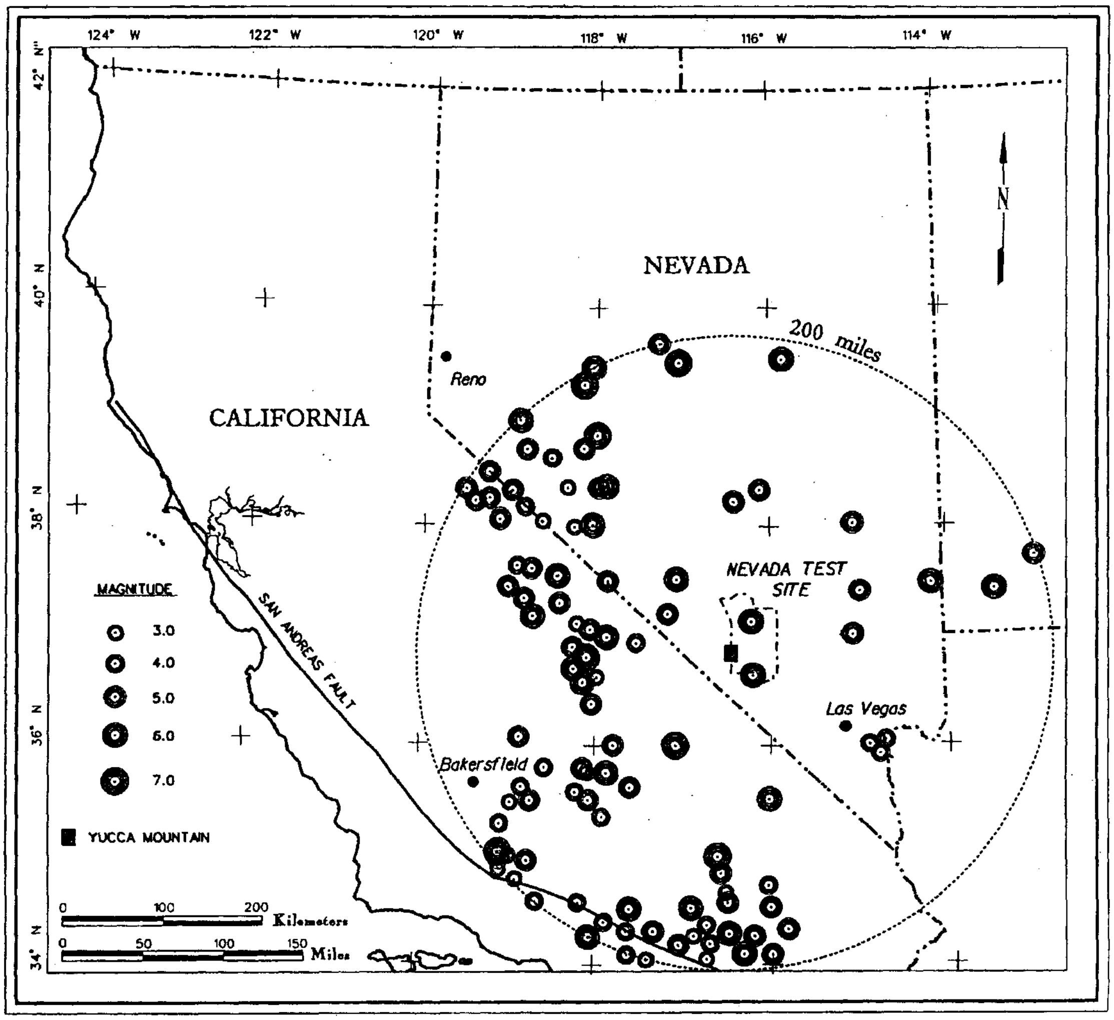

Figure 7-14. Magnitude 3 or Greater Earthquakes Within 320 Km (200 Miles) of Yucca Mountain from 1850 to 1992 (Modified from DOE95a)

Based on a return period of 12,700 years, Bechtel Nevada estimates that for the adjacent Nevada Test Site there is a 0.55 probability of at least one earthquake of magnitude 6.8 or greater occurring in the next 10,000 years (SHO97).

DOE has not considered seismicity to be a significant factor in repository safety performance. Seismic effects are not considered in previous total system performance assessments (DOE94a, DOE95b) because DOE believes that they will have virtually no effect underground. Dowding and Rozen (DOW78) examined empirical evidence of damage to 71 rock tunnels in Alaska, California and Japan from earthquake shaking. From this analysis, the authors concluded that, for peak surface accelerations which would cause heavy damage to above ground structures, there was only minor damage to tunnels. No tunnel damage was observed for peak surface accelerations of less than approximately 0.2g and only minor tunnel damage occurred when the peak surface acceleration was less than 0.5g.

DOE quantitatively analyzed the variation of ground motion with depth using both stochastic and empirical methods (DOE94e). Peak surface accelerations were shown to be reduced by a factor of two at a depth of about 400 m.

DOE considered tectonism in the TSPA-VA released in 1998, including the effects of parameter variability (DOE98). NRC included the effects of fault displacement impacts and seismic rockfall impacts on waste packages in TPA 3.1 (NRC97c).

In its 1996 Phase 3, Yucca Mountain Total System Performance Assessment, the Electric Power Research Institute (EPRI) did not include consideration of earthquakes since it was concluded that "...tectonic activity is not expected to significantly impact repository integrity" (EPR96).

The National Academy of Sciences (NAS) supports DOE's view that seismic effects on underground excavations are usually less severe than on surface facilities (NAS95, p. 93). In addition, NAS states that while the timing of seismic effects is unpredictable, the consequences of such events are boundable for performance assessment purposes (Ibid., p. 94). The NAS further notes that it is possible for the hydrologic regime to be affected either adversely or favorably by seismic events.

The technical community did not agree with DOE's position on structural deformation and seismicity presented in TSPA-95. Subsequently, in May 1996, a meeting of involved groups was held to review and seek agreement on defensible tectonic models based on available data. The group included DOE, NRC, the Advisory Committee on Nuclear Waste (ACNW), the Nuclear Waste Technical Review Board, the USGS, the State of Nevada, the EPRI, and the Center for Nuclear Waste Regulatory Analyses (CNWRA) (NRC97a). Of 11 proposed models, the group agreed that only five were supported by existing data. Agreement on the five supportable models was not unanimous nor was agreement on the relative importance of the five models. In addition, some of the models may be independent and some may be subsets of others. The five viable alternative models are:

- Deep detachment fault (12-15 km)
- Moderate detachment fault (6-8 km)
- Planar faults with block deformation
- Pull-apart basin[18]
- Amargosa shear

The pull-apart basin model proposed by the USGS and the Amargosa shear model proposed by the State of Nevada are based on buried or blind seismic sources at Crater Flat and involve the greatest seismic risk. These seismic sources are not included in DOE's Probabilistic Seismic Hazards Analysis which was used as a partial basis for the conclusions reached in TSPA-95. Depending on proximity to the repository, the Amargosa shear could result in an earthquake with magnitude $M_w \geq 7.8$ and accelerations exceeding 1 g (NRC97a). More recently, CNWRA stated that apatite-fission-track dating from Bare Mountain and Striped Hills does not support the USGS reconstruction of the Amargosa shear model (McK96). CNWRA believes that the pull-apart basin model is more tenable but requires additional direct observations of basin-bounding and cross-basin strike-slip faults.

Additionally, DOE argued that future tectonic events are unlikely to significantly alter the hydrologic characteristics of the Yucca Mountain site. This argument is based on the position that the current state of faults and fractures at the site is the result of cumulative tectonic events. However, CNWRA posits that a single tectonic event can cause significant changes in hydrologic characteristics. The DOE argument is valid only for characteristics resulting from cumulative events and not for the most recent single tectonic event (NRC97a).

7.1.1.6 Fractures (Adapted from DOE95a)

Closely allied with tectonic issues is the consideration of fractures in the rocks surrounding the repository. An extensive fracture network can provide fast paths both for influx of water into the repository for overlying strata and egress of water potentially contaminated with radionuclides through underlying strata. To develop an understanding of fractures, studies have been

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[18] A pull-apart basin is a structural depression formed by localized extension along strike-slip fault zones. The basin is formed in the brittle upper crust above a horizontal detachment in the lower crust (NRC97a).

conducted to examine the age and connectivity of fractures primarily in a portion of the Tiva Canyon Tuff. Outcrop studies were conducted for a number of units. The studies were designed to define the general orientations of fracture sets over all of Yucca Mountain and to establish the relationship of fracture sets to regional tectonic history. A few studies of the vertical continuity of fractures have been conducted in the Paintbrush nonwelded unit. These are designed to examine changes in fracture pattern as a function of stratigraphy (DOE95a).

Four sets of tectonic fractures with consistent orientation were identified within the Paintbrush Group. In addition, a set of sub-horizontal joints with variable strikes and dips of less than 10 degrees exists. These fracture sets may have originated as extension joints, many of which have been subsequently been reactivated. It has been postulated that the fractures developed as a mountain-wide response to far-field stresses rather than local movement of structural blocks. However, data to support this hypothesis conclusively are limited (DOE95a).

Fracture widths are defined both by rock wall separation and actual fracture aperture. Rock wall separation is the distance between the fractured surfaces without reference to any infilling with secondary minerals. Aperture includes the effects of any infilling and is the amount of open space remaining. Wall separations are typically one to 10 mm from the surface to a depth of about 200 m. Surface fractures are 50 to 75 percent filled with caliche which reduces the aperture to one to two mm. Below about 10 m from the surface, the fractures are 40 to 50 percent filled, primarily with quartz and calcite (DOE95a).

Studies of surface fractures have led to the following general conclusions (DOE97c, SWE96):

- Fracture intensity is a function of lithology, variation in the degree of welding in the tuffs, and, to a lesser extent, proximity to faults

- Connectivity of the fracture network also depends largely on the degree of welding and the lithology

- Width and intensity of fractured zones vary around faults and are related to fault complexity

The degree of welding within the Paintbrush Group has the greatest effect on the overall character of the fracture network with fracture intensity and network connectivity being least in nonwelded or poorly-welded units.

Subsurface studies have indicated that correlation with surface features diminishes as the depth increases because:

- Some faults which displaced units in the Topopah Spring Tuff became inactive before the overlying Tiva Canyon Tuff was deposited
- Many faults are discontinuous so that the displacement may die out between observation points
- Faults commonly spread upward resulting in differing surface and subsurface geometries (DOE97c)

7.1.1.7 Volcanism (Adapted from DOE95a)

To assess the possibilities of disruptive volcanic events, the nature and history of volcanism in the area must be understood. Yucca Mountain consists of silicic volcanic rocks originating from the Timber Mountain caldera complex to the north. A resurgence of silicic volcanism is unlikely since the activity that formed the rocks at Yucca Mountain ceased millions of years ago. However, basaltic volcanism has taken place more recently. Basaltic volcanism is commonly accompanied by the intrusion of dikes into the surrounding rocks and could pose the potential for intrusion into the repository itself if such volcanism occurred close to the repository. Magmatic intrusions could mobilize waste and/or alter ground-water pathways. The volcanic history of the Yucca Mountain area is discussed below.

Yucca Mountain is composed of Miocene volcanic rocks erupted from the overlapping Silent Canyon, Claim Canyon, and Timber Mountain calderas between 11 and 15 million years ago. The silicic volcanic tuffs that comprise Yucca Mountain are typical of mid-Tertiary basin and range extensional tectonics in southern Nevada. Yucca Mountain, at the depth of the proposed repository, is comprised of units of the Paintbrush Tuff, a major outflow ignimbrite of the Claim Canyon caldera segment of the Timber Mountain caldera complex (Figure 7-15). During the late Neogene (two to 10 Ma) and Quaternary (0 to two Ma) Periods, small-volume, mostly polygenetic, basaltic centers produced lava flows, air falls, and cinder cones in the area. The silicic and basaltic volcanism are described below.

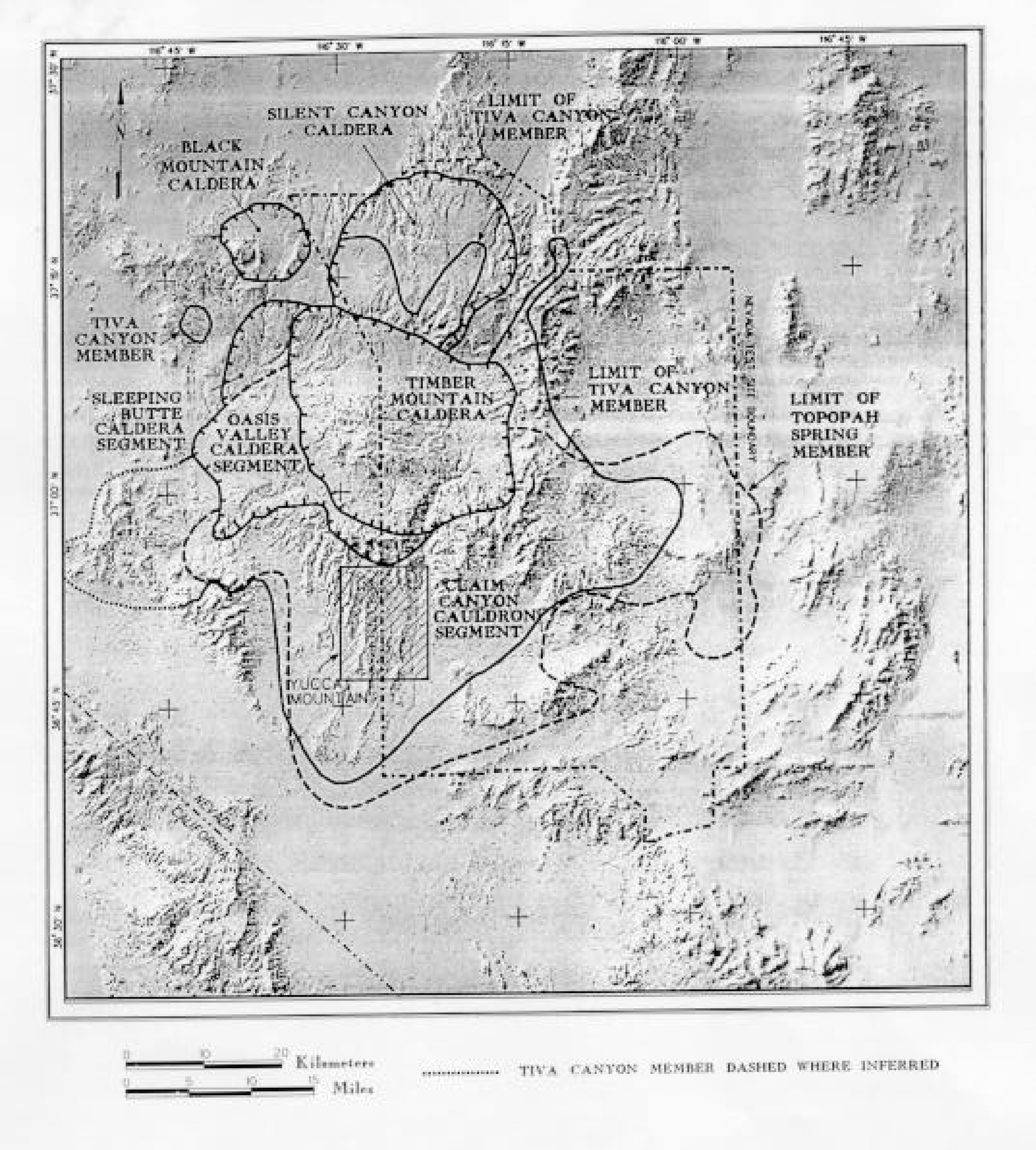

Figure 7-15. Index Map Showing Outlines of Calderas in the Southwestern Nevada Volcanic Field and the Extent of the Tiva Canyon and Topopah Spring Tuffs of the Paintbrush Group (Modified from DOE95a)

Silicic Volcanism

The silicic volcanism in the Yucca Mountain area is part of an extensive, time transgressive pulse of mid-Cenozoic volcanism that occurred throughout much of the southwestern United States. Yucca Mountain is in the south-central part of the SNVF, a major Cenozoic volcanic field covering an area of over 11,000 km^2. Magmatism in the region was distributed in linear belts parallel to the convergent plate margin during the Mesozoic Era. In the southwestern United States, a pause or disruption in the belts about 80 Ma formed the Laramide magmatic gap or hiatus, which lasted until renewed silicic magmatism began in the northeastern part of the Great Basin about 50 Ma. Sites of eruptive activity migrated south and southwest across parts of Nevada and Utah, with eruptive centers distributed along arcuate east-west trending volcanic fronts. The most intensive eruptions were at the leading edge of the migrating front, with the most voluminous silicic volcanic activity in the Yucca Mountain area occurring between 11 and 15 Ma. Silicic magmatic activity in the area ceased about 7.5 to 9 Ma. The Yucca Mountain area marks the southern limit of time-transgressive volcanic activity.

Between 10 and 13 Ma, there were two significant changes in the regional volcanic and tectonic patterns: the southern migration of volcanism halted and the composition of the volcanic activity changed. Diminished silicic-eruptive activity migrated in less systematic patterns to the southwest and southeast, leaving a conspicuous amagmatic gap from the southern edge of the Nevada Test Site south to the latitude of Las Vegas.

Should volcanism occur in the future, the type of volcanism (basaltic or silicic) is potentially significant, since silicic eruptions are more explosive. The DOE claims that there has been no silicic volcanism in the Yucca Mountain Region since about 7.5 Ma at the Stonewall Mountain caldera more than 100 km northwest of Crater Flat and since nine Ma at the closer Black Mountain caldera (60 km northwest of Crater Flat). Consequently, DOE has concluded that the potential for future silicic volcanism is negligible (DOE96e). However, work by NRC suggests that silicic pumice with an age of 6.3 ±0.8 Ma (based on zircon fission track data) existed beneath basalts in Crater Flat. This is at odds with the DOE position that post-caldera silicic eruptions had not occurred near the proposed repository site (NRC97a). Subsequently, NRC reported that, based on argon isotope dating, the age of the silicic material was 9.1 ±3 Ma, which correlates with the eruptions from the Black Mountain caldera (NRC97b). On the basis of this information, NRC concluded that silicic volcanism did not need to be considered in evaluating the probability and consequences of igneous activity at Yucca Mountain.

Basaltic Volcanism

Two episodes producing basaltic-volcanic rocks have been defined in the Yucca Mountain area, both occurring after the majority of the silicic volcanism ended. The first, marked by basalt of the silicic episode (BSE), consists of basalt-rhyolite volcanism postdating most silicic eruptions of the Timber Mountain-Oasis Valley (TM-OV) complex. The second episode is comprised of spatially-scattered, small-volume centers marked by scoria cones and lava flows of alkali basalt, ranging in age from about 10 Ma to less than 10,000 years. These post-caldera basalts of the Yucca Mountain Region are divided into older post-caldera basalts (OPB) and younger post-caldera basalts (YPB). The locations of basalts in the Yucca Mountain Region with ages of less than 12 Ma are shown in Figure 7-16 (NRC96). (The cited ages of some of the occurrences reported by NRC differ slightly from those reported by DOE. The differences are not substantive.)

The BSE crops out throughout the Yucca Mountain area and is identified by several characteristics: 1) a close association (in time and space) with activity of the TM-OV complex, 2) all centers of the BSE are large-volume eruptive units (<3km^3 dense-rock equivalent—the largest centers are in the ring-fracture zone of the Timber Mountain caldera), and 3) a wide range of geochemical composition. The BSE occurs in three major groups:

- **Mafic Lavas of Dome Mountain** (age 10.3 ±0.3 Ma) are exposed in the moat zone of the Timber Mountain caldera and comprise the largest volume of basaltic rocks
- **Basaltic Rocks of the Black Mountain Caldera** overlap some units of the caldera in age
- **Basaltic Volcanic Rocks, Yucca Mountain Area** include the basaltic andesite of Skull Mountain (dated 10.2 ±0.5 Ma), the basalts of Kiwi Mesa, and Jackass Flats

The second episode of basaltic volcanism, marked by the post-caldera basalt of the Yucca Mountain Region, occurred at sites either well removed from the eruptive centers of the TM-OV complex or younger than the silicic-magmatic activity. These sites generally consist of small volume (<1 km^3) centers marked by clusters of scoria cones and lava flows.

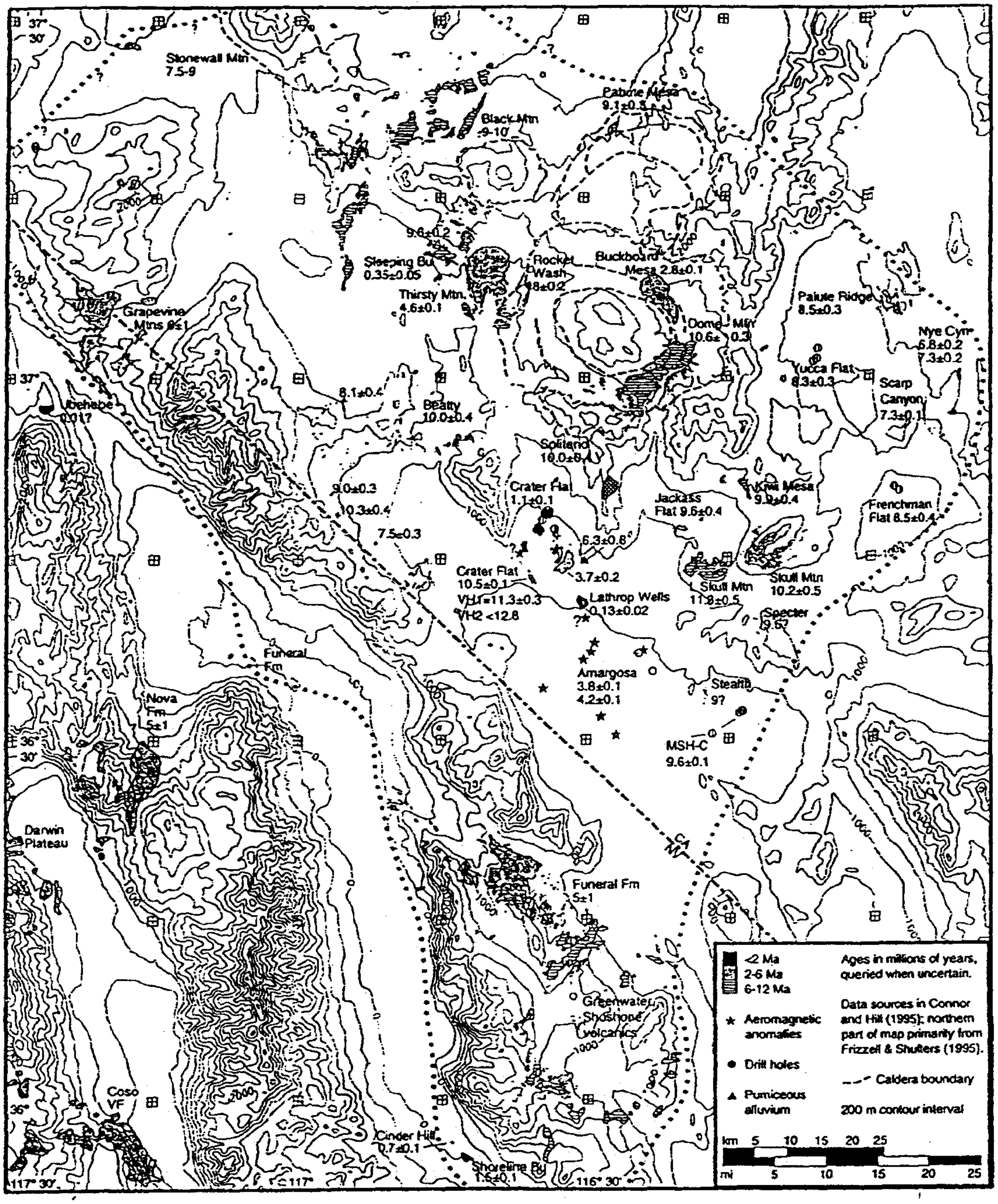

Figure 7-16. Distribution of Basalts in the Yucca Mountain Region with Ages of Less Than 12 MA (NRC96). Dotted line defines boundary of Yucca Mountain/Death Valley isotopic province where basalts have same relatively unique isotopic structure.

The OPB were produced along either north-northwest trending Basin and Range faults or at the intersection of Basin and Range faults with the ring-fracture zone of older calderas. These range in age from 10.4 to 6.3 Ma and are represented at four localities:

- **Rocket Wash**, thin, basalt lava flows (8.0 ±0.2 Ma) occur at the edge of the ring-fracture zone of the Timber Mountain caldera
- **Pahute Mesa**, three separate but related basalts (with ages ranging from 8.8 ±0.1 to 10.4 ±0.4 Ma) occur at the intersection of faults with the ring-fracture zone of the Silent Canyon caldera
- **Paiute Ridge**, dissected scoria cones and lava flows (8.5 ±0.3 Ma) are associated with intrusive bodies occurring at the interior of northwest-trending graben; the related Scarp Canyon basalt (8.7 ±0.3 Ma) crops out west of Nye Canyon
- **Nye Canyon**, three surface basalts (6.3 ±0.2 Ma, 6.8 ±0.2 Ma, and 7.2 ±0.2 Ma) and a buried basalt (8.6 Ma) occur in the Canyon.

The second eruptive cycle, resulting in the YPB, usually occurred at clusters of small-volume centers aligned along predominantly northeast structural trends. These eruptions occurred from 4.9 Ma to as recently as 0.004 Ma and are represented at the following localities (in decreasing age):

- **Thirsty Mesa**, a thick accumulation of fluidal lava and local feeder vents erupted onto a pre-existing Thirsty Canyon Group ignimbrite (welded tuff) plateau (ages of 4.6, 4.68 ±0.3, and 4.88 ±0.4 Ma are reported for various samples)
- **Amargosa Valley**, cuttings from a buried basalt gave ages of 3.85 ±0.05 and 4.4 ±0.07 Ma
- **Southeast Crater Flat** basalt lavas (4.27 to 3.64 Ma) are the most areal-extensive of the YPB
- **Buckboard Mesa** basaltic andesite (3.07 ±0.29 to 2.79 ±0.10 Ma) erupted from a scoria cone in the northeast part of the ring-fracture zone of the Timber Mountain caldera and from nearby fissures
- **Quaternary Basalt of Crater Flat** consists of a series of four northeast trending basalt centers extending along the axis of Crater Flat including the Little Cones (0.76 ±0.20 to 1.1 ±0.3 Ma), the Red and Black Cone centers (1.55 ±0.15 to 0.84

±15 Ma and 1.09 ±0.3 to 0.80 ±0.06 Ma, respectively), and the Makani Cone (1.66 ±0.5[19] to 1.04 ±0.03 Ma)

- **Sleeping Butte Centers** are two small volume (<0.1 km^3) basaltic centers about 2.6 km apart with an estimated age of 0.38 Ma based on recent argon isotope dating measurements

- **Lathrop Wells Center**, the youngest and most thoroughly studied center of basaltic volcanism, involved multiple eruptions over more than 100,000 years

Three alternative models involving various chronologies of volcanic events have been proposed by DOE to explain the eruptive history of the Lathrop Wells volcanic center. These include a four-event eruption model (eruption at >0.13, 0.08 to 0.09, 0.065, and 0.004 to 0.009 Ma), a three-event eruption model (eruptions at 0.12 to 0.14, 0.065, and 0.004 to 0.009 Ma), and a two-event eruption model (eruptions at 0.12 to 0.14 and 0.004 to 0.009 Ma). Exact dating of the eruptions has been problematic and the exact number and timing of the eruptions is not certain, but the youngest eruption is believed to be less than 10,000 years old. This most recent activity was restricted to minor ash deposits (TRB95).

Summary

The majority of the silicic volcanic rocks that form the most important units in the Yucca Mountain stratigraphic section were deposited about 11 to 15 Ma. This silicic volcanism ceased about 7.5 Ma. Silicic volcanism was followed by two subsequent episodes of basaltic volcanic rock formation. In the first episode, basalts of the silicic episode were deposited about 10 Ma. In the second or post-caldera episode, smaller eruptions occurred beginning 8 to 10 Ma and continuing to near present time. The youngest basaltic rocks at the Lathrop Well volcanic center have ages between 4,000 and 9,000 years.

Both DOE and NRC agree that a future occurrence of silicic volcanism is highly unlikely and therefore the consequences of such an event need not be considered in system performance assessment. However, DOE and NRC have not reached agreement on the treatment of igneous activity associated with possible future basaltic volcanic events.

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[19] This value appears to be an anomaly and will be investigated further.

Given the history of volcanism in the Yucca Mountain Region, there is some probability that a volcanic event can either intersect the repository footprint and directly affect the waste or that a nearby intrusive dike can indirectly affect the natural and engineered barriers. In TSPA-93 (DOE94a), DOE used available data to estimate the impact of indirect magmatic effects, such as heating or attack by aggressive volatiles on waste packages, when contact of the waste packages with magma does not occur. Assuming that the waste packages were vertically emplaced, such that the thermal loading they produced was 57 kW/acre, the magmatic effect on peak drinking water doses is virtually indistinguishable from a case in which magmatic effects are not considered.

In subsequent activities to address the stochastic uncertainty associated with the possibility that a future magmatic event may intersect the repository, DOE convened a panel of 10 experts and used a formal elicitation process to develop disruption[20] probability estimates (DOE96f). Results of the elicitation include (DOE97a):

- A mean annual disruption probability of 1.5×10^{-8}
- A 95 percent confidence interval of 5.4×10^{-10} to 4.9×10^{-8}
- Upper and lower bounds of 10^{-10} to 10^{-7}

The NRC has taken a different tack in establishing the probabilities of volcanic disruption. The NRC approach considers spatial patterns of basaltic volcanism, regional recurrence rates of volcanic activity, and structural controls on volcanism in the Yucca Mountain Region (NRC96). Using two different measures to assess the impact of structural controls on volcanism (density of high dilation-tendency faults and horizontal gravity gradients), two methods to assess spatial-temporal distributions (near-neighbor and Epanechnikov kernel methods) and regional recurrence rates varying from two to 10 volcanoes per million years, calculated probabilities based on NRC's bounding approach ranged from 1×10^{-8} to 2×10^{-7} volcanic disruptions per year (NRC96).

Based on a homogeneous Poisson model (i.e., with a time invariant rate), the probability of at least one volcanic disruption event occurring in 10,000 years, using DOE's estimated maximum (95 percent confidence) disruption rate of 4.9×10^{-8}/y, is 0.0005. Based on the maximum disruption rate estimated by NRC of 2×10^{-7}/y, the probability of at least one disruption is 0.002 in 10,000 years.

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[20] Disruption is the physical intersection of magma with the potential repository volume (DOE97a).

In its 1996 Phase 3, Yucca Mountain Total System Performance Assessment, EPRI did not include consideration of volcanism (EPR96). This position was based on an assessment made by one member of the expert panel — one of 10 volcanologists sponsored by DOE — who estimated that the annual probability of a magmatic intrusion into the proposed repository is 1.0×10^{-8}.

Scientists at UNLV, supported by the State of Nevada, have considered a number of alternative modeling approaches to volcanism. (See, for example, HO96 and HO95.) Using a non-homogeneous Poisson model (i.e., with a time varying rate), Ho estimated the probability of at least one disruption in 10,000 years to lie between 0.0014 and 0.03.

DOE plans to conduct further analyses related to igneous activity in the TSPA-VA scheduled for publication in 1998 (DOE97b).

7.1.1.8 Geologic Stability Issues

The NAS Panel report states that the Yucca Mountain site will exhibit long-term geologic stability on the order of one million years (NAS95). This implies that the contribution of geology to overall system performance can be assessed for that time period. The Panel therefore concludes that there is no need to arbitrarily select a shorter compliance evaluation period, such as 10,000 years. The Panel recommends "...that compliance assessment be conducted for the time when the greatest risk occurs, within the limits imposed by long-term stability of the geologic environment."

This section examines the Panel's assertion of long-term geologic stability and related issues. Factors addressed include characteristics of the geologic and hydrologic systems implied by the Panel's concepts of "stable" and "boundable;" validity of the assertion of stability; and the significance of stability to the occurrence, magnitude, and evaluation of peak dose. Geologic stability does not imply absence of geologic activity or absence of changes in geologic processes, but rather that any changing characteristics of the system do not introduce uncertainties of sufficient magnitude to compromise the ability to perform credible analyses of future repository performance.

Characterization of Geologic Stability by the NAS Panel

The NAS report (NAS95) does not specifically define geologic stability. The existence of stability is discussed six times in the report, in different ways:

> *The geologic record suggests that [the time frame during which the geologic system is relatively stable or varies in a boundable manner] is on the order of one million years.* (Executive Summary, page 9)
>
> *...the long-term stability of the fundamental geologic regime [is] on the order of one million years at Yucca Mountain.* (page 55)
>
> *The long-term stability of the geologic environment at Yucca Mountain ... is on the order of one million years.* (page 67)
>
> *The time scales of long term geologic processes at Yucca Mountain are on the order of one million years.* (page 69)
>
> *The time scale for long-term geologic processes at Yucca Mountain is on the order of approximately one million years*. (page 72)
>
> *The geologic record suggests that [the time frame over which the geologic system is relatively stable or varies in a boundable manner] is on the order of about one million years.* (page 85)

These characterizations of geologic stability are quite similar, although some are expressed in terms of the geologic regime itself and others are described in terms of the processes that operate on or within that regime. These two assertions are not necessarily the same. For example, characteristics of the geologic regime that are important to peak dose evaluation might remain stable while tectonic and other natural processes and events continue in the future, even varying from past characteristics. Alternatively, natural processes and events may continue in the future as they have occurred in the past (i.e., the processes and events exhibit stability), while the effects they produce may change the features of the geologic regime that are important to peak dose evaluation. Conditions in which past and continuing tectonic movement produces differential movement of deep geologic structures might cause changes in the hydrologic regime important to the occurrence of the peak dose. The various expressions of stability used in the Panel's report imply no significant change in either the geologic regime or in the processes and events that affect the characteristics of that regime.

The Panel's report does not explicitly justify the assertion of million-year stability by providing a synopsis and interpretation of the geologic record. Some of the references cited in the report contain information about the geologic record (e.g., DOE's Site Characterization Plan for the Yucca Mountain site (DOE88)), but none of the cited references interprets the record to indicate a million-year stability of the geologic regime or the processes associated with it.

Existing Documentation Related to Stability

Existing documentation does not directly address long-term stability of the natural features of Yucca Mountain and its environs. Until quite recently, the DOE documents containing information about the geologic features of the Yucca Mountain site anticipated that evaluations of site suitability would be made in accord with DOE's 10 CFR Part 960 Site Suitability Regulations and anticipated safety performance of a repository at the site would be evaluated in terms of EPA's 40 CFR Part 191 regulations and NRC's 10 CFR Part 60 regulations. Under this regulatory framework, the time period of concern is 10,000 years.

The 10,000-year time frame for compliance with EPA's 40 CFR Part 191 regulation was selected by the Agency because it was short compared to long-term factors, such as tectonic motion, that might affect and change in ways that could not be characterized, the natural environment conditions important to regulatory compliance evaluations. On the other hand, the time period was long enough to bring into consideration, at least in principle, factors such as seismicity that are important in geologic time scales and might affect repository performance.

The DOE has, in many Yucca Mountain project documents, implied geologic stability or the equivalent for time periods of 10,000 years. The State of Nevada believes, however, that the record does not justify such a conclusion. For example, the State asserts in its comments (NEV85) on DOE's draft Environmental Assessment (DOE84) for the Yucca Mountain site, that DOE's conclusion that "neither major tectonic activity nor the resumption of large-scale silicic volcanic activity in the area near Yucca Mountain is likely in the next 10,000 years" is premature, based on existing evidence. The State also asserts that "possible hydrovolcanic activity at Yucca Mountain has not been sufficiently evaluated" (NEV85, Volume II, page 125).

In general, the documents of record show controversy over the stability of the geologic regime and associated natural processes and events at the Yucca Mountain site. The controversy stems both from opposing interpretations of the available data by DOE and the State of Nevada and by differing definitions of geologic stability. To some extent, the opposing viewpoints reflect the institutional positions of the parties involved; nonetheless, the uncertainties in the data permit alternative interpretations to be made and controversy to persist.

Interpretation of the Geologic Record Related to Stability

The geologic history of the area provides the basis for assertions concerning the stability of the geologic regime for Yucca Mountain and its vicinity. Site characterization activities for DOE's Yucca Mountain project, and other activities unrelated to the Yucca Mountain project (e.g., commercial characterization of natural resource potential), have yielded an extensive data base concerning geologic features and the geologic record of the region. The most comprehensive data available for judging the geologic stability of the Yucca Mountain site are presented in DOE's Site Characterization Plan (DOE88).

Such data do not, however, definitively resolve the question of the long-term stability of the geologic regime. Such issues can be resolved only in context, through the expert judgment of the involved parties. The NAS Panel's assertion of long-term geologic stability at Yucca Mountain for the next million years is an example of such judgment.

The basis for the Panel's judgment of the geologic stability of Yucca Mountain over the next one million years is the conclusion that the properties and processes of the geologic regime important to repository performance "... are sufficiently understood and stable over the long time scales of interest to make calculations [of repository performance] possible and meaningful" (NAS95, page 68). The relevant properties and processes include the radionuclide inventory of the waste, the influx of water to the repository, migration of the water and its contained waste materials from the repository to the ground water, and subsequent dispersion and migration of contaminated ground water to the regional biosphere. The Panel considers it possible, for example, to estimate, with acceptable uncertainty, concentrations of wastes in ground water at various locations and times for the purpose of a bounding safety assessment.

The assertion of geologic stability implies a judgment that the basic features of the geologic regime that affect waste release and transport will remain as they are, or change in a limited and reasonably predictable fashion, over the next million years. In other words, phenomena that would substantially and unpredictably change the current, relevant geohydrologic regime are not expected. Such phenomena would include tectonic motion, seismicity, and volcanism sufficient to change the features of the geologic regime that govern radionuclide release and transport.

The Panel's assertions also imply that the geologic and hydrologic features of the site and region can and will be characterized in a way that allows repository performance to be reliably projected on the basis of current conditions. Two of the parameters cited by the panel as important to predicting the performance of the repository—water influx to the repository and dispersion and migration of ground water in the biosphere—are demonstrated by DOE modeling studies (DOE95b, herein also termed TSPA-95) to be highly important to estimating potential health effects from the repository. However, these two parameters are currently among the least well-known of the parameters related to repository performance.

The DOE performance assessment reports indicate that these hydrologic parameters will be extremely difficult to evaluate reliably. As DOE notes in TSPA-95, direct observation of water infiltration rates is not possible. Consequently, TSPA-95 treats the infiltration rate to the repository as an uncertain parameter. Bounding values, consistent with the NAS Panel's concept of bounding, can be established, but the bounds may have to be narrowed considerably from present ranges to be meaningful to the process of determining compliance.

This situation raises an issue not addressed directly by the NAS Panel: Can key performance-related parameters be adequately characterized? The long-term geologic stability of the Yucca Mountain site may be less important to evaluating repository performance than the actual values of those parameters most significant to its performance. As the example given above demonstrates, the variability of a parameter such as infiltration rate presents an obstacle to characterizing reliably the long-term risks to the critical group. In addressing the overall question of long-term repository performance, the uncertainty associated with these factors may be much more significant than the uncertainty associated with the long-term geologic stability of the site.

Summary of Evidence for Stability

The information presented in this chapter generally supports the NAS Panel's assertion that the fundamental geologic regime at Yucca Mountain will remain stable over the next one million years. The overall picture that emerges from the data is that the site and region had a highly dynamic period of volcanism, seismicity, and tectonic adjustment in the past, but these processes and events have matured into a system in which the magnitudes, frequencies, locations, and consequences of such phenomena can be bounded with reasonable confidence relative to assessing the long-term repository performance.

The possible exception to this finding is the chance that on-going processes and events are producing differential changes to the geologic and hydrologic regimes that are currently unrecognized but could affect repository performance and potential radiation risks for affected populations in the future. For example, on-going tectonic processes and movements could potentially have different effects on the geologic and hydrologic regimes near the surface and at depth, and the at-depth changes may not be readily recognizable. At present, tectonic movement in the area varies by location but falls generally within the range of four to 10 mm/year (DOE95a). Over one million years, an annual tectonic movement of 10 mm/year will produce a total translation of location of about 5 miles. If all of the elements of the geologic and hydrologic regime important to repository performance and dose estimation do not move together in space and time, the differential movement could invalidate the results of performance and exposure assessments. The potential for differential movement and its consequences are not yet addressed.

Perspective on the Significance of Stability of the Geologic Regime

A judgment that the geologic regime at Yucca Mountain will be stable for one million years enhances confidence in the results of model-based assessments of the effects of natural processes and events over that time frame on repository performance. Long-term natural phenomena may not, however, control repository performance or uncertainties in performance assessment results. Uncertainties in other factors involved in performance projections may ultimately control the reliability of the projections.

The existence of long-term geologic stability can assure reliable estimation of long-term peak doses only if stability-related issues are confirmed to dominate repository performance and numerical values of relevant parameters have been established with confidence. As discussed subsequently in Section 7.3, DOE's total system performance assessments indicate that the rate of infiltration of water to the repository and the dilution and dispersion characteristics of ground water containing radioactive contamination released from the repository are the dominant factors in repository performance and dose assessment. If the repository design is altered, these may no longer be the dominant factors.

These findings suggest that geologic stability is not significant unless it affects these water-flow parameters (e.g., through differential tectonic displacement). However, the scope of DOE's performance assessments is to date highly limited. In addition, DOE carefully notes (Chapters 9 and 10, DOE95b) that the approach to dose estimation used in its TSPA evaluations does not correspond to that considered by the NAS Panel. Overall, DOE's performance assessments to date have not attempted to establish a perspective on geologic stability and other factors that might affect repository performance and radiation doses for one million years.

The DOE's performance assessments to date for Yucca Mountain have emphasized release of nuclides from the repository over a 10,000-year time frame, in response to the requirements of EPA's 40 CFR Part 191 regulations, which were applicable until enactment of the WIPP Land Withdrawal Act. Experience in evaluating repository performance over a 10,000-year time frame (DOE94a, DOE95b) has shown that repository conditions must be assessed at, or near, the time when key performance parameters, such as temperature, may be at their peak values. The 10,000-year time frame encompasses the time of highest uncertainty in the effect of repository design factors important to waste isolation and safety performance. These uncertainties may have a greater effect on predicting long-term repository performance and regulatory compliance than a natural process or event, such as an earthquake or a volcanic eruption. This is due to the high degree of uncertainty in the "nominal" dynamics and performance of the repository's barriers and the low probability of a major natural process or event occurring.

Beyond 10,000 years, however, the technical factors associated with repository design features that dominate performance issues earlier may become less important to determining regulatory compliance at the time of peak dose. If the engineered barrier system is likely to have failed in the long term, radionuclides will be available for transport to the environment. The DOE performance assessment report by Intera, Inc. (DOE94b) states that variations in assumptions and conditions for waste package degradation produce less than a 20 percent variation in results for a 10,000 year assessment period and less than a 10 percent variation in results for a 100,000 year period. Supplemental calculations in DOE94c show that peak doses and releases at the accessible environment boundary over a one million-year period are generally unaffected by waste package lifetimes up to 100,000 years. It is in the time period beyond 10,000 years that the issue of long-term geologic stability becomes more important to repository performance.

In summary, three periods of repository conditions in the future can be characterized, with geologic stability being maintained throughout all three. In the first, short-term period, lasting about 100 to 1,000 years, the repository is characterized by intact waste canisters, high temperatures and temperature gradients which serve as driving forces for transients such as chemical reaction, and the retention of short-lived and long-lived radioactivity in the canisters. Infiltrating water may or may not contact the canisters.

In the intermediate period, with a duration between 1,000 and 10,000 years, gradients are diminishing or gone and the engineered features of the repository are degrading. During this time, canisters are corroding; only long-lived radioactivity remains; some of the radioactivity from the waste is released from the canisters, but most is retained within the repository. Infiltrating water contacts and transports radioactive waste.

In the long-term period, from 10,000 to 1,000,000 years, the repository is essentially an isothermal ore body of the oxides, hydroxides, or carbonates of waste-package materials at ambient conditions. Infiltrating water seeps through the bed of oxides and transports long-lived radioactivity to the environment, where the radioactive contamination is diluted and dispersed by ground-water flow processes.

Given this perspective, the transitional processes associated with the engineered features and heat-emission characteristics of the repository will essentially be complete in one percent of the elapsed time of a regulatory period of 1,000,000 years. Therefore, the physical state of the repository at 10,000 years can serve as the initial condition for the assessment of repository performance and dose assessment under conditions of geologic stability for a period of 1,000,000 years.

7.1.2 Hydrologic Features

7.1.2.1 Unsaturated Zone Hydrology

The region beneath the surface of Yucca Mountain in the vicinity of the proposed repository is characterized by a very thick unsaturated zone, ranging in thickness from about 500 to 750 m. The variable thickness is produced by the combined effects of rugged topography and a sloping water table. The presence of a thick unsaturated zone is desirable for siting an underground waste repository because ground water, and any contaminants it might carry, generally travels more slowly through the unsaturated zone than through the saturated zone. The thicker the unsaturated zone, the longer contaminants will take to reach the water table.

In this document, and in the literature generally, the term unsaturated flow actually means partially-saturated flow, since by definition there can be no water flow through a totally dry medium. Unsaturated ground-water flow is more complex than fully-saturated flow because it involves the simultaneous movement of water, air and water vapor. For unsaturated media, the measure of permeability is called the effective hydraulic conductivity. The effective hydraulic conductivity, and hence the rate of fluid flow, through any given partially-saturated porous medium depends on the degree of saturation of that medium. The higher the saturation, the greater the quantity of water that can flow through it, all other factors (saturated hydraulic conductivity, hydraulic gradient, etc.) being equal. As the degree of saturation reaches 100 percent, the effective hydraulic conductivity approaches fully-saturated hydraulic conductivity. The dependency between degree of saturation and effective hydraulic conductivity is complex, due to the nonlinearity of the relationship.

The dependence of unsaturated flow on the degree of saturation is important to understand when reading the following sections of this document because some of the phenomena described are not intuitively obvious. An example of this is described later, where it is stated that water moving downward in the partially-saturated zone encounters zones of increased effective porosity, which may act as barriers to further downward flow. It may at first seem counterintuitive that a zone of increased porosity could act as a flow barrier until one considers that a geological zone with a high porosity possesses a low capillary suction potential. If this zone is overlain by a zone which has a lower porosity and thus a higher capillary potential, water entering the upper zone will be retained there as a result of capillary equilibration. These conditions will prevail until the gravitational force overcomes the capillary force in the upper zone as more water enters, which usually happens when the bottom of the upper zone becomes nearly saturated, allowing water to flow into the lower zone.

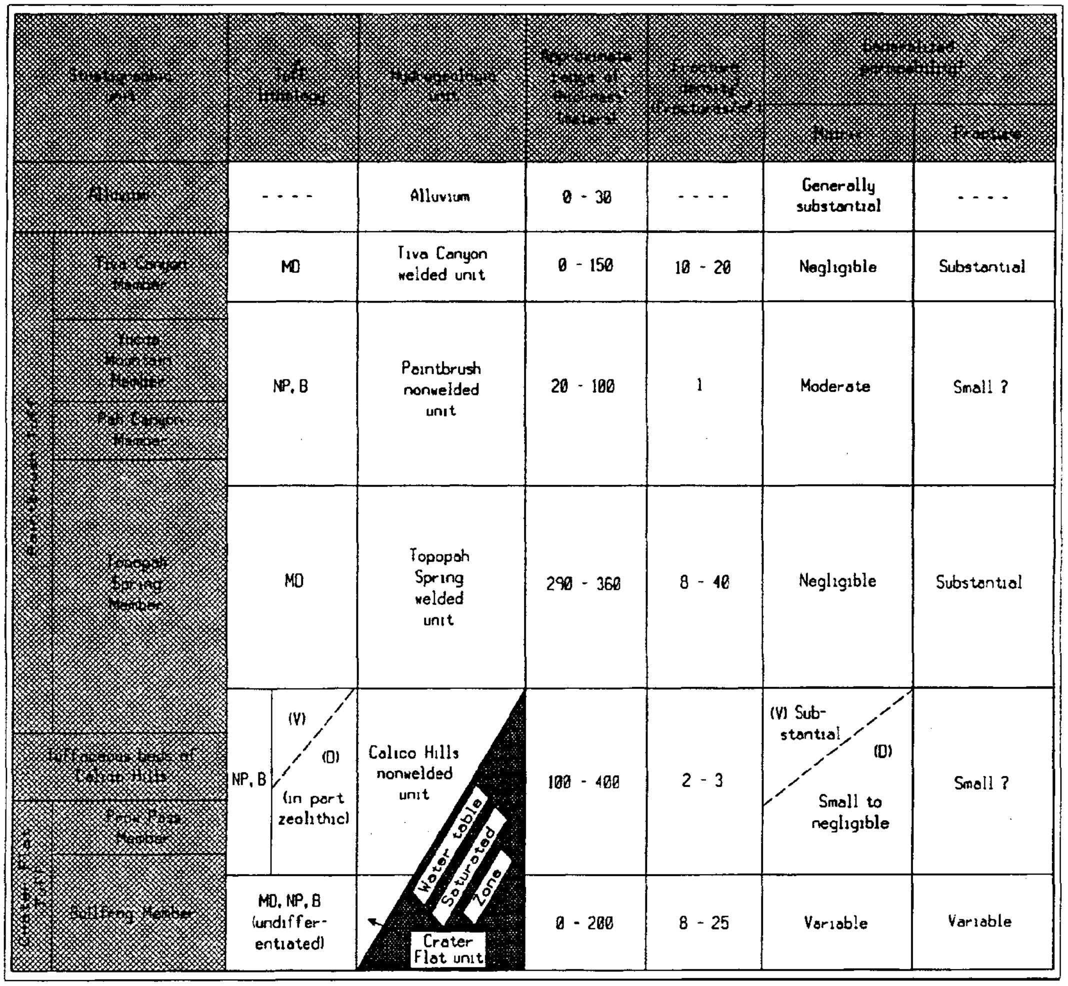
A sequence of nonwelded porous tuffs that overlies the Topopah Spring Member (Section 7.1.1) may act as a natural capillary barrier to retard the entrance of water into the fractured tuffs. A similar sequence of nonwelded tuffs underlies the Topopah Spring Member. These underlying nonwelded tuffs locally contain sorptive zeolites and clays that could be an additional barrier to the downward transport of some radionuclides from a repository to the water table.

The proposed repository is surrounded by and crossed by numerous strike-slip and normal faults with varying amounts of offset (LBL96). The repository would be located largely, if not entirely, within what is known as the "central block" as described below (see Figure 7-8). The structural geology of this block is less complex than in the surrounding area, although one extensive, nearly vertical normal fault has been mapped in the block (Ghost Dance Fault). The central block of Yucca Mountain is a large block beneath the center of the Yucca Mountain ridge and is bounded on its west side by the Solitario Canyon fault, a major north-striking normal fault with greater than 100 m of offset. West of this fault is a chaotic, brecciated and faulted west-dipping zone caused by drag on the fault. A zone of imbricate normal faults forms the eastern boundary of the central block. These faults are west-dipping and have vertical offsets of about two to five m. Northwest striking strike-slip faults also occur in the area, such as the one forming the northern boundary of the central block, beneath Drill Hole Wash. The concept of a central block should not, however, be taken to imply that the central block or the proposed repository area is free of faults (USG84a).

Unsaturated Zone Hydrogeologic Units

The detail of the layered volcanic rock sequence beneath Yucca Mountain is very complex. The various rock units can be separated into a small or large number of units depending upon the scale and aims of a particular study. For the purposes of this document, the unsaturated zone is considered to consist of six hydrogeologic units, based on their physical properties. This grouping and the description of the six units are based primarily on USG84a, except where otherwise referenced. Additional data regarding matrix and fracture properties are presented in the hydrogeologic database developed in DOE95c.

The physical properties within each formation vary considerably, largely due to variation in the degree of welding of the tuffs. In most cases, physical property boundaries do not correspond to rock-stratigraphic boundaries. However, it is the physical properties that largely control water occurrence and flow; the hydrogeologic subunits into which the volcanic sequence is separated are different than the lithological units outlined in Section 7.1.1.3. The hydro-geologic units are, in descending order, Quaternary Alluvium (Qal), the Tiva Canyon welded unit (TCw), the Paintbrush nonwelded unit (PTn), the Topopah Spring welded unit (TSw), the Calico Hills nonwelded unit (CHn), and the Crater Flat unit (CFu). Figure 7-17 illustrates these hydrogeologic units and some of their characteristics. They are described in detail in the following paragraphs.



Stratigraphic unit		Tuff lithology	Hydrogeologic unit	Approximate range of thickness¹ (meters)	Fracture density² (fractures/m³)	Generalized permeability³	
						Matrix	Fracture
Alluvium		- - - -	Alluvium	0 - 30	- - - -	Generally substantial	- - - -
Paintbrush Tuff	Tiva Canyon Member	MD	Tiva Canyon welded unit	0 - 150	10 - 20	Negligible	Substantial
	Yucca Mountain Member Pah Canyon Member	NP, B	Paintbrush nonwelded unit	20 - 100	1	Moderate	Small ?
	Topopah Spring Member	MD	Topopah Spring welded unit	290 - 360	8 - 40	Negligible	Substantial
Tuffaceous beds of Calico Hills		NP, B (V) / (D) (in part zeolitic)	Calico Hills nonwelded unit	100 - 400	2 - 3	(V) Substantial / (D) Small to negligible	Small ?
Crater Flat Tuff	Prow Pass Member						
	Bullfrog Member	MD, NP, B (undifferentiated)	Crater Flat unit	0 - 200	8 - 25	Variable	Variable

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

Figure 7-17. Unsaturated Zone Hydrogeologic Units (USG84a)

Structural features, although they are not hydrogeologic units in the same sense as stratigraphic units, are mappable, have certain measurable hydraulic characteristics, and may have a significant effect on unsaturated zone flow. Because these structural features are regarded as important components of the unsaturated hydrologic system, they are described later in this section.

Qal. Unconsolidated alluvium underlies the washes that dissect Yucca Mountain and forms the surficial deposit in broad inter-ridge areas and flats nearby. Thickness, lithology, sorting, and permeability of the alluvium are quite variable; particles range in size from clay to boulders, and in places the unit is moderately indurated by caliche. Alluvial and colluvial deposits generally have small effective hydraulic conductivity, large specific retention, and large effective porosity as compared to the fractured rocks. Therefore, a large proportion of the water infiltrated into the alluvial and colluvial material is stored in the first few meters of the soils and is lost to evaporation during dry periods. The saturated permeability of alluvium generally is substantial compared to the tuff units.

TCw. Lying immediately beneath the Qal is the Tiva Canyon welded unit, consisting of devitrified ash-flow tuffs ranging from 0 to 150 m in thickness across the site. The TCw is the densely to moderately-welded part of the Tiva Canyon Member of the Paintbrush Tuff. This unit is the uppermost stratigraphic layer that underlies much of Yucca Mountain; it dips 5° to 10° eastward within the central block, resulting in a relatively planar eastward-sloping, dissected land surface. The unit is absent in some washes and is about 150 m thick beneath Yucca Crest. This unit has a fracture density of 10 to 20 fractures/m^3 and small matrix permeability. Saturated matrix hydraulic conductivity has been estimated at about $2x10^{-6}$ m per day (m/d); the effective hydraulic conductivity is thought to be lower, as saturation is estimated to range from 60 - 90 percent. Neither bulk rock nor fracture hydraulic conductivities are well characterized for this unit.

PTn. The Paintbrush nonwelded unit is situated below the TCw unit and consists of the nonwelded and partially welded base of the Tiva Canyon Member, the Yucca Mountain Member, the Pah Canyon Member, the nonwelded and partially-welded upper part of the Topopah Spring Member, and associated bedded tuffs. All are part of the Paintbrush Tuff. The unit consists of thin, nonwelded ash-flow sheets and bedded tuffs that thin to the southeast from a maximum thickness of 100 m to a minimum thickness of about 20 m. The unit dips to the east at 5° to 25°; the dip at any location depends on the tilt of the faulted block at that site. In the central block, the dip rarely exceeds 10°. In the vicinity of the central block, this unit crops out in a narrow band along the steep west-facing scarp along Solitario Canyon.

Tuffs of this unit are vitric, nonwelded, very porous, slightly indurated, and in part, bedded. The unit has a fracture density of about one fracture/m^3. Saturated hydraulic conductivities of five core samples of the matrix have a geometric mean of about $9.0x10^{-3}$ m/d. Porosities average about 46 percent, but some porosities are as much as 60 percent. The rocks of this unit are moderately saturated, with an average value of about 61 percent. However, water contents are relatively large; the mean volumetric water content is about 27 percent and the mean water content by weight is about 19 percent. The maximum values reported are: saturation, 80 percent; volumetric water content, 42 percent; and water content by weight, 36 percent.

TSw. The Topopah Spring welded unit consists of a very thin upper vitrophyre, a thick central zone consisting of several densely welded devitrified ash-flow sheets and a thin lower vitrophyre of the Topopah Spring Member of the Paintbrush Tuff. The unit, which varies from 290-360 m in thickness, is densely- to moderately-welded and devitrified throughout its central part. The TSw contains several lithophysal cavity zones that generally are continuous, but vary appreciably in thickness and stratigraphic position. The TSw is also intensely fractured.

The Topopah Spring Member is the thickest and most extensive ash-flow tuff of the Paintbrush Tuff. The central and lower densely-welded, devitrified parts of the Topopah Spring welded unit are the candidate host rock for a repository. This part of the unit contains distinctive subunits that have abundant lithophysal gas cavities within the central block. The saturated hydraulic conductivity of the matrix of this unit generally is small and has a mean of about 3.0×10^{-6} m/d.

Because of the densely fractured nature of this unit, bulk hydraulic conductivity is substantially greater than matrix hydraulic conductivity. Saturated horizontal hydraulic conductivity of the rock mass is about one m/d for a 120-meter interval of the TSw that was packed off and tested at Well J-13 (see Figure 7-18 for bore hole locations), about six km east of Yucca Mountain. Because of the marked contrast between the matrix and the bulk hydraulic conductivities in this unit, values of the bulk hydraulic conductivity from Well J-13 (USG83) and borehole UE-25a#4 probably represent the hydraulic conductivity of the fractures in this unit. The large bulk hydraulic conductivity of this unit probably promotes rapid drainage of water. The amount of flow carried in the fractures with respect to the matrix has been estimated to range between 10 - 95 percent (GEO97).

The effect of lithophysal cavities on the hydrologic properties of the TSw is not well understood. Total porosity is much greater where lithophysal cavities are more abundant than in those sections that are free of these cavities. Overall unsaturated hydraulic conductivity probably is decreased by the presence of these cavities. These cavities commonly are several centimeters in diameter, filled with air, and form capillary barriers with the fine grained matrix. In effect, the cavities decrease the transmissive cross-sectional area, decrease effective porosity, and consequently, decrease the effective hydraulic conductivity.

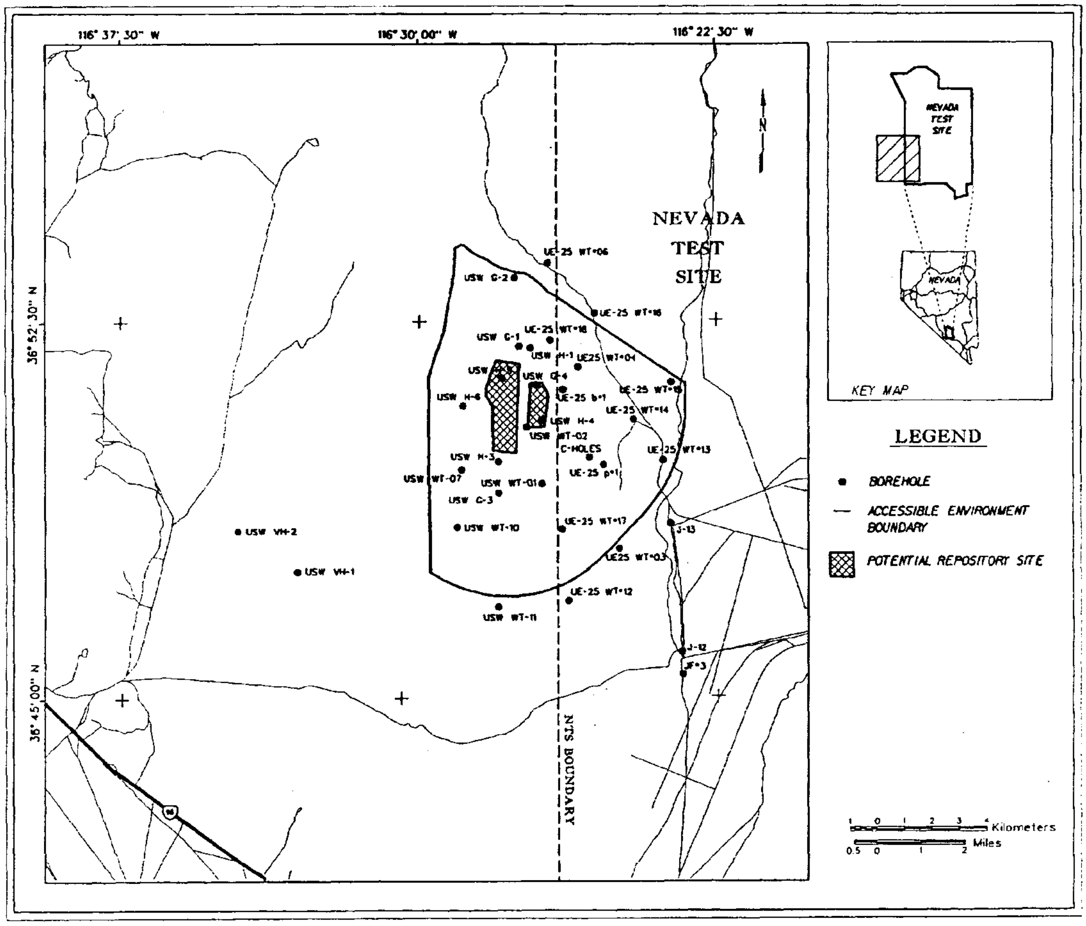


Figure 7-18. Locations of Deep Boreholes in the Vicinity of Yucca Mountain (USG96a)

CHn. Beneath the TSw unit is a series of non- to partially-welded ash-flow tuffs called the Calico Hills nonwelded unit. Locally, these may be vitric (CHnv) or zeolitized (CHnz). The CHn includes the following components, in descending order:

1. A nonwelded to partially-welded vitric layer, locally zeolitic, that is the lowermost part of the Topopah Spring Member of the Paintbrush Tuff.
2. Tuffaceous beds of Calico Hills.
3. The Prow Pass Member of the Crater Flat Tuff, which is nonwelded to partially-welded where it occurs in the unsaturated zone beneath the central block.

4. The nonwelded to partially-welded upper part of the Bullfrog Member of the Crater Flat Tuff where it is above the water table.

In the vicinity of the central block, this unit crops out in a narrow band along the steep west-facing scarp along Solitario Canyon. Both vitric and devitrified facies occur within the CHn. As described below, the permeability of the vitric facies is substantially greater than that of the devitrified facies. Alteration products in the devitrified facies include zeolites (most abundant), clay, and calcite (rare). Because this facies is mostly zeolitic, it is hereafter referred to as the zeolitic facies. Thickness of the zeolitic facies generally increases from the southwest to the northeast beneath Yucca Mountain. Beneath the northern and northeastern parts of the central block, the entire unit is devitrified and altered.

Both the vitric and zeolitic facies of the CHn are very porous, with a mean porosity of about 37 percent for the vitric facies and 31 percent for the zeolitic facies. Saturations in this unit generally are greater than 85 percent, with a mean value for the zeolitic facies of about 91 percent.

A significant difference exists in values of vertical hydraulic conductivity of the matrix between the vitric and zeolitic facies of the CHn. The mean vertical hydraulic conductivity of the matrix of the vitric facies is 4.0×10^{-3} m/d. The geometric mean of the vertical hydraulic conductivity of the matrix of the zeolitic facies is about 8.0×10^{-6} m/d. The marked contrast in vertical hydraulic conductivities of the two facies probably is the result of extensive argillization in the zeolitic facies, which tends to decrease permeability.

CFu. In approximately the southern half of the central block, the lowermost unit in the unsaturated zone is the Crater Flat unit. This unit consists of the unsaturated welded and underlying nonwelded parts of the Bullfrog Member of the Crater Flat Tuff. No differentiation is made between the welded and nonwelded components of the Crater Flat unit because of the limited extent of the unit in the unsaturated zone beneath the central block, and therefore, its probable limited effect on the unsaturated flow system. Beneath the central block, the thickness of the CFu ranges from 0 to 160 m. Little is known about the unsaturated hydrologic properties of the unit, but it is assumed that the properties are similar to those of the nonwelded and welded counterparts higher in the section.

Structural Features

As previously described, the central block of Yucca Mountain is bounded on three sides by faults. Because these major faults and fault zones transect the full thickness of the unsaturated zone, they may by hydrologically significant either as flow barriers or as flow pathways. The variation in unsaturated hydraulic properties of these features have in most cases not been measured. However, some inferences can be made, based on the physical properties of the welded and nonwelded tuff units and on observations of drill cores.

The welded units are relatively brittle. Open faults have been observed in cores even from below the water table. Conversely, the nonwelded units generally are more ductile than the welded units and more readily produce a sealing gouge material. Fault zones are less common in the Calico Hills nonwelded unit. In general, hydraulic conductivity varies greatly along the faults and is greater in welded units than in nonwelded units (USG84a).

Knowledge of the permeability of the numerous faults which cross Yucca Mountain is important because some faults may act as conduits for rapid vertical flow in the unsaturated zone. This possibility is especially critical in areas in which such faults may intercept large amounts of lateral flow and divert this flow downward, potentially into the repository. Evidence for the permeability of the faults in and around the proposed repository area is mixed. Studies performed to date indicate that particular faults are barriers, while other faults are more permeable (LBL96). It is also possible that a particular fault may be relatively impermeable in some areas of the fault plane, and relatively permeable in others. Factors which may reduce permeability of faults include development and alteration of fault gouge, deposition of fracture coating materials on fault surfaces, and the juxtaposition of permeable and nonpermeable units by movement along the fault plane. Faulting can also create zones of enhanced permeability where the rock around the faults is highly fractured or brecciated.

Studies in the Exploratory Studies Facility (ESF) indicate that the permeability of the Bow Ridge fault is about the same as measured with air permeability testing of highly permeable bedded tuff formations or highly fractured welded units. Also, the geothermal profile in borehole ONC#1 shows that the geothermal profile is offset by several degrees as the borehole passes through the Bow Ridge fault zone. This indicates that the fault may be highly permeable to gas or moisture flow which decreases the temperature in that region (LBL96).

Evidence from other faults indicates that they may act as low permeability barriers. For instance, the water body observed at borehole SD-7 is thought to be perched over a zeolitic layer and prevented from moving laterally by the presence of the Ghost Dance fault. A similar hypothesis has been invoked to explain perched water in a borehole intersected by a splay of the Solitario Canyon fault. This conclusion is corroborated by pneumatic pressure data taken in borehole UZ-7a, which appear to show a degree of anisotropy in the fault which is consistent with a permeability barrier, at least in the horizontal direction (LBL96).

Another indication that some faults at the site may act as permeability barriers is obtained from potentiometric surface measurements. For instance, the potentiometric surface elevation on the western side of the Solitario Canyon fault is approximately 40 m higher than on the eastern side of the fault. This gradient could only be maintained if the Solitario Canyon fault is somehow a permeability barrier to flow (LBL96).

The ESF has provided data and observations regarding the structural features within Yucca Mountain. Prior to the construction of the ESF, detailed geological and structural cross-sections were prepared. As-built cross sections prepared from data and observations from the ESF show that geologic sections drawn prior to construction compare favorably with results from tunneling. These findings indicate that the lithostratigraphy, and to a lesser extent structure, of this are well-characterized and predictable. Detailed information on the results of ESF geological mapping is available in BOR96 and BOR96a. These publications provide detailed fracture pattern analysis including measurements of trace length, orientation, continuity, roughness, aperture, and mineral infilling. From ESF studies, three main fracture sets are reported; two are approximately vertical and strike north-south, and east-west, while the third fracture set is close to horizontal. BOR96 reports that the open distance between fracture faces averages 2.3 mm over the entire fracture population. The largest aperture is 91 mm, although this is anomalously large in this population; 67 percent of the fractures are closed (0 mm). For fractures with an aperture greater than zero, the average is 7.2 mm. The fracture population includes measurements from the Tiva Canyon Tuff, the Paintbrush Tuff, and the Topopah Spring Tuff. The repository horizon is generally more fractured, containing an average of about four fractures per meter, but typically ranges from about two to six fractures per meter (LLNL96).

A common feature in some horizons in the volcanic rocks are lithophysal cavities, which are voids in the rock presumably created by gases exsolved from cooling lavas and pyroclastic deposits. In the Tiva Canyon and Topopah Spring Tuffs, lithophysae are mostly concentrated into stratiform zones, but they also occur adjacent to lithophysal zones and sporadically in nonlithophysal zones. The cavities range in size from less than one centimeter (cm) to greater than 1.4 m. Fractures demonstrate several different relationships with lithophysal cavities. Fractures that intersect and terminate in lithophysal cavities are common. This, and other evidence, suggest that lithophysal cavities may locally influence fracture propagation (BOR96, BOR96a).

Ground Water Flow In The Unsaturated Zone

Water flow and storage in the unsaturated zone is three-dimensional and is controlled by the structural, stratigraphic, thermal, and climatological setting. The dynamics of water-air-vapor flow in the layered, fractured rock unsaturated zone beneath Yucca Mountain are complex and highly uncertain at this time. In the unsaturated zone, water is present both in liquid and vapor phases within the interstitial, fracture, and lithophysal openings. Hydrogeologic features that probably affect flow significantly in the unsaturated zone include the presence of fractured porous media, layered units with contrasting properties, dipping units, bounding major faults, and a deep water table. These features probably result in the occurrence of phenomena such as flow in both fractures and matrix, diversion of flow by capillary barriers, lateral flow, perched ground water zones, and vapor movement.

Infiltration Rates

The ultimate source of water in the unsaturated zone at Yucca Mountain is precipitation on the mountain. The spatial and temporal relationships between infiltration and recharge are complex, because of the hydrogeologic variability of Yucca Mountain. Some water that infiltrates returns to the surface by interflow; another part is returned to the atmosphere by evapotranspiration. A small quantity that is not evaporated, or discharged as interflow, percolates deep into the unsaturated zone and becomes net infiltration or percolation. The terms “infiltration” and “percolation” are used frequently, sometimes interchangeably, in literature about the Yucca Mountain unsaturated zone. For the purposes of this report, “infiltration” is used to describe the amount of water which enters Yucca Mountain at the ground surface, while “percolation” is used to describe the amount of water which actually penetrates deep enough into the mountain to reach the repository horizon and below. The difference between the two terms lies mainly in the partitioning of part of the infiltration flux into the vapor phase, which may then be recirculated to the atmosphere.

At Yucca Mountain, the infiltration rate is both spatially and temporally variable. Because the quantity of net infiltration that percolates through different paths is quite variable, estimated average recharge rates do not represent percolation rates through specific flow paths. Spatial variations of infiltration depend mostly on variations in the properties of surficial units, topography, the intersection of faults with the surface, and the presence of local fracturing. Temporal variations in infiltration rate are related to the seasonality and relatively infrequent precipitation events in the arid climate of Yucca Mountain. Temporal variations in the infiltration rate have also occurred over a much larger time span, reflecting long term climate changes.

Knowing the temporal and spatial variability of the percolation rates is crucial to modeling efforts because of the importance of the relationship of infiltration rate to horizontal and vertical permeabilities of the various units and the effect this has on whether or not significant lateral flow occurs in the unsaturated zone. The higher the actual infiltration rate, the greater the likelihood of significant lateral flow. Such lateral flow could result from a combination of two factors. The first factor is that infiltrating water may encounter zones of lower relative permeability as it moves downward. The second factor is that in many of the units, the relative permeability is far greater in the direction parallel to bedding than the direction perpendicular to it. The anisotropic permeability may cause lateral flow of mounded water away from the area in which it accumulates. Lateral flow is important because it could transmit water to structural features which would then move the water downward, possibly acting as a conduit to divert large amounts of water flowing downward through a small area. Such flow paths could direct water into and through the repository or away from it.

The actual quantity of net infiltration or percolation beneath the surface of Yucca Mountain has not been accurately determined. The percolation flux is a difficult parameter to determine for low flux regions such as Yucca Mountain. There are currently no reliable direct measurements that can be made to determine this important parameter (LBL96). Existing estimates have been obtained from a mixture of indirect methods involving field testing and modeling of various processes at different scales. Data exist to suggest that the flux reaching the repository horizon through the matrix is relatively small. Relatively low matrix saturations measured in the upper portion of the TSw suggest that much of the moisture which infiltrates into the TCw does not reach the TSw (LBL96). Data from the ESF show that no weeping fractures were found, even in the region where perched water is found in boreholes. (Note, however, that because of ventilation equipment inside the ESF, much of any such moisture might be removed from the ESF as water vapor). Furthermore, no moisture was observed infiltrating into the radial boreholes of Alcove 1 of the ESF after storm events, even though the boreholes are located close to the land surface in the highly fractured and broken TCw formation (LBL96). However, other data suggest that the percolation flux may reach the repository level mainly through episodic fracture flow. These data include observation and testing of extensive bodies of perched water located below the repository horizon, as well as measurements of bomb-pulse isotope levels from atmospheric nuclear testing which show that some water in the unsaturated zone is relatively young (LBL96).

Estimates of net infiltration vary from slightly negative (net loss of moisture from the mountain) to about 10 mm/yr (LBL96). USG84a reports that net infiltration flux probably ranges from 0.5 to 4.5 mm/year, based on estimates of earlier workers for various localities in the Yucca Mountain area. Flint and Flint (FLI94) provide preliminary estimates of spatial infiltration rates that range from 0.02 mm/yr, where the welded Tiva Canyon unit outcrops, to 13.4 mm/yr in areas where the Paintbrush nonwelded unit outcrops. The bulk of the area above the repository block is underlain principally by the Tiva Canyon member. The DOE’s 1995 Total System Performance Assessment (DOE95b) concludes that, if the predominant flow direction is vertical, then the average infiltration through the repository block, using the average infiltration rates of Flint and Flint (FLI94), would be 0.02 mm/yr. If, on the other hand, the predominant flow direction has a significant lateral component due to material property heterogeneity and/or anisotropy and the sloping nature of the hydrostratigraphic unit contacts, then the average net infiltration rate over the repository block could be as high as some weighted average of the infiltration rates inferred from FLI94. The 1995 TSPA (DOE95b) also reports that the average, spatially-integrated infiltration rate is about 1.2 mm/yr; most of this infiltration occurs along the Paintbrush outcrop in the washes north of the repository block.

Recently, several lines of evidence have converged to alter the prevailing view regarding the magnitude of infiltration/percolation rates beneath Yucca Mountain, with the most recent estimates being revised upward from previous work. The newer estimates of percolation are around five mm/yr, with a range of one to 10 mm/yr (LANL96, LBL96). Recent isotopic analyses of rock samples from the ESF are consistent with a percolation rate of five mm/yr (LANL96, LBL96). Profiles of temperature vs. depth of water in boreholes are consistent with a range of infiltration rates from one to 10 mm/yr (LBL96). Three-dimensional modeling results of percolation flux at the repository horizon using the latest available spatially varying infiltration map indicate percolation fluxes on the order of five to 10 mm/yr. The expert elicitation panel estimates for mean infiltration rates range from 3.9 to 12.7 mm/y (GEO97). The effect of uncertainty in infiltration and percolation flux rates is examined in the discussion of the unsaturated zone conceptual model.

Conceptual Model(s)

The first detailed conceptual model of unsaturated zone flow at Yucca Mountain was proposed in USG84a. Since then, the majority of the data collected has been in general agreement with these ideas and concepts (LBL96). Most subsequent conceptualizations of unsaturated zone behavior are largely refinements of this model, revised to accommodate newly-acquired data (Figures 7-19 and 7-20). Newly-acquired data include isotopic analyses, concentration ratios of ions dissolved in matrix rocks and perched water zones, calcite fracture fillings, and thermal modeling of vertical temperature gradients. Perhaps the most significant change from early conceptual models has been the recent acquisition of new isotopic data which indicate the presence of “fast paths” for water moving through the unsaturated zone. This topic is discussed in more detail in a subsequent section.

The following presentation of the unsaturated zone flow conceptual model is taken primarily from USG84a. Where appropriate, the published literature is referenced when describing refinements or revisions that have been made to the USG84a model. The following conceptual model is presented as if it were an established physical reality. Bear in mind, however, that the proposed model is probably not the only reasonable description that could be made of the system. Following the description of the conceptual model is a discussion of critical unknowns, their effects on unsaturated zone flow, and results of numerical modeling studies.

Percolation of infiltrated water through the exposed fractures of the Tiva Canyon welded unit is relatively rapid because of the large fracture permeability and small effective porosity of this unit compared to the alluvial material. Therefore, a large proportion of the infiltrated water normally is percolated sufficiently deep within the fractured tuff to be unaffected by the evaporation potential that exists near the surface. Depending on the intensity of the infiltration, percolation downward through the Tiva Canyon welded unit may occur without a significant change in rate.

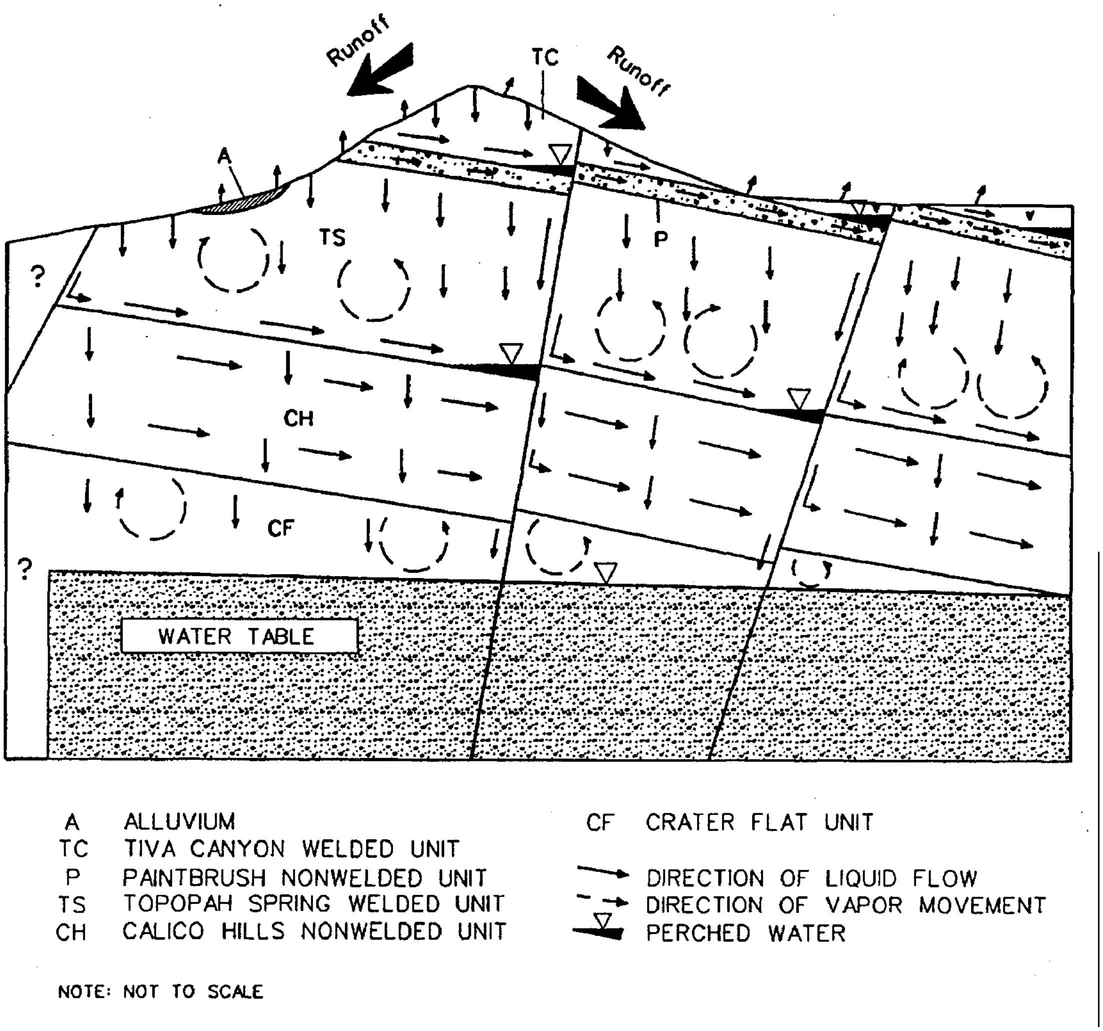


Figure 7-19. Early Conceptual Model of Ground-water Flow in the Unsaturated Zone at Yucca Mountain (USG84a)

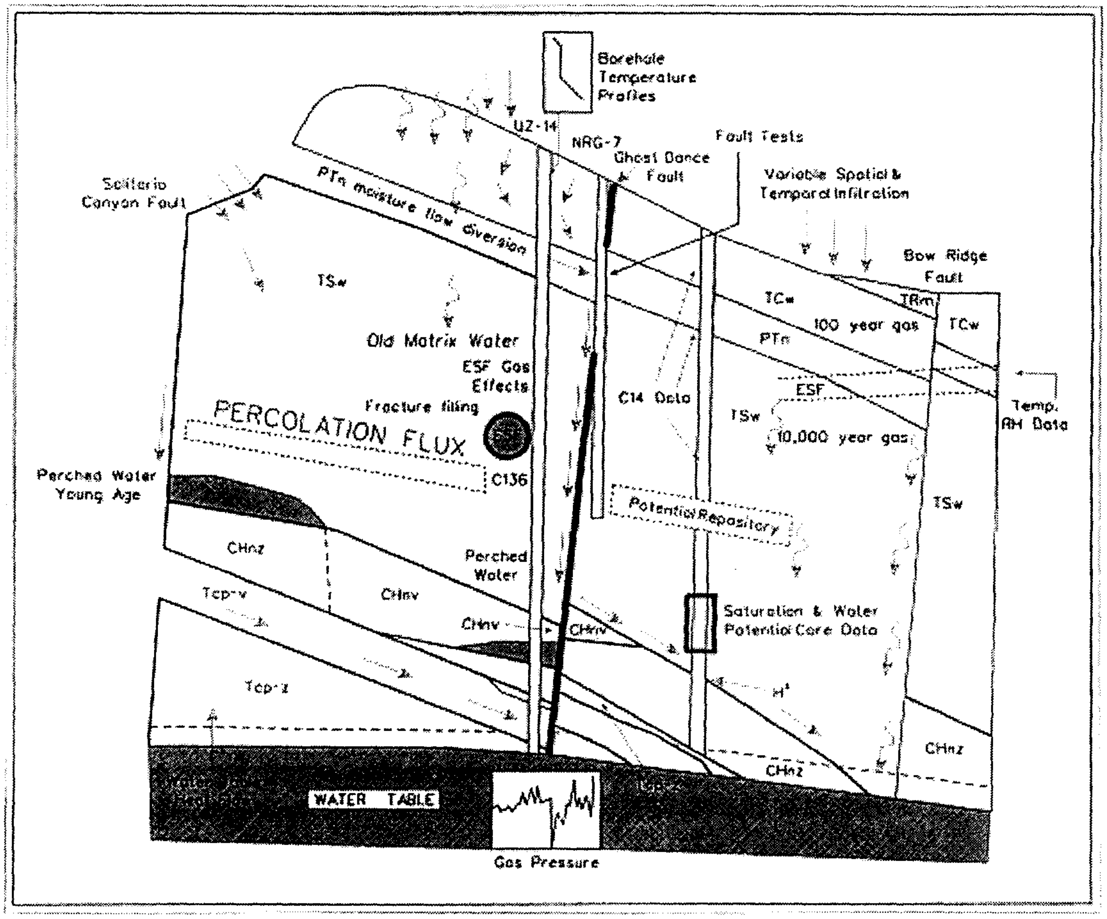


Figure 7-20. Current Conceptual Model of Ground-water Flow in the Unsaturated Zone at Yucca Mountain (LBL96)

A small proportion of the water percolating through the fractures slowly diffuses into the matrix of the Tiva Canyon welded unit. Downward flow in the matrix is very slow because of the small effective hydraulic conductivity of the matrix. During dry periods, some of the diffused water flows back into the fractures and probably reaches the land surface by vapor diffusion. The mass of water involved during this process is likely to be negligible compared to the percolating water.

The densely fractured Tiva Canyon unit, with small matrix porosity and permeability, overlies the very porous, sparsely fractured Paintbrush unit. A marked contrast in material properties exists at the contact between these two units; depending on the magnitude of the infiltration flux, this contrast could impart a significant lateral component of flow. Flow of water through fractures of the Tiva Canyon unit occurs rapidly until it reaches the contact. At this point, the velocity is significantly decreased because of the greater effective porosity and lesser hydraulic conductivity of the Paintbrush unit. As a result, lateral, unsaturated flow of water above this contact can occur. Perched water may occur above this unit if displacement along faults has created significant differences in permeability on opposite sides of the fault.

The saturated hydraulic conductivity of the Paintbrush nonwelded unit in the direction of dip is 10 to 100 times greater than saturated hydraulic conductivity in the direction normal to the bedding plane. The combination of dipping beds and differences in directional permeability creates a downdip component of flow. The magnitude of this component depends on the magnitude of the principal hydraulic conductivity ratio. The permeability contrast may be sufficient to decrease vertical percolation into the underlying Topopah Spring welded unit to almost zero. In this case, water would flow laterally downdip until structural features are encountered that create perching conditions or provide pathways for vertical flow.

As water moves downward through the PTn, the effect of high porosity and low fracture density progressively moves water from fractures into the matrix. Except for areas where fast paths may exist (such as faults), beyond a certain depth in the PTn, flow may be almost entirely in the matrix. Travel times through the matrix of the PTn are thought to be relatively long because the matrix of this unit appears to act as a “sponge” which dampens out episodic infiltration pulses.

Water flows from the matrix of the Paintbrush nonwelded unit into the fractures or matrix of the underlying Topopah Spring welded unit. Owing to the thickness of this unit, it is hypothesized by ROB96 that water moving through the fractures eventually diffuses into the matrix and moves very slowly downward. An exception is the second subunit of the TSw (ROB96). In contrast to this conceptualization, the unsaturated zone expert evaluation panel estimated that up to 95 percent of the flow in the Tsw could remain in the fractures (GEO97).

Flow enters the Calico Hills nonwelded unit either from the matrix of the Topopah Spring welded unit or through structural flowpaths. How much flow occurs in the fractures of the lower part of the Topopah Spring unit is unknown, and therefore their potential to contribute to flow into the Calico Hills unit is also uncertain.

The nature of flow at the contact between the Topopah Spring welded unit and the Calico Hills nonwelded unit depends on whether the vitric or zeolitic facies of the Calico Hills unit is present. The permeability and effective porosity of the vitric facies are much greater than those of the matrix of the Topopah Spring unit, which may result in a capillary barrier where those units are in contact. Conversely, the permeability of the zeolitic facies is about the same as for the matrix of the Topopah Spring unit, resulting in continuity of matrix flux across the contact.

Flux within the Calico Hills unit may occur with some lateral component of downdip flux, because of the existence of layers with contrasting hydraulic conductivity in the unit. A large scale anisotropy probably is caused by intercalation of tuffs with alternately large and small permeability and by compaction.

Water that flows downdip along the top of the Calico Hills unit slowly percolates into this unit and slowly diffuses downward. Fracture flow is known to occur near the uppermost layers of the Calico Hills unit, but diffusion into the matrix may remove the water from the fractures deeper in the unit and thereby limiting flow mostly to within the matrix, except along the structural flowpaths. It is possible, however, that fractures provide significant avenues for rapid flow through this unit. Beneath the southern part of the block, the Crater Flat unit occurs between the Calico Hills unit and the water table. Included are the welded part and underlying nonwelded part of the Bullfrog Member of the Crater Flat Tuff.

Fluxes along many structural flowpaths are probably larger than within the units they intersect. The Calico Hills unit is more ductile than the overlying Topopah Spring unit, which may give the Calico Hills unit fracture sealing properties. In addition, because of the lesser shear strength of this unit compared to that of the Topopah Spring, gouge formation along faults and shear zones is more common. These properties may result in a smaller fracture conductivity in the Calico Hills unit. In the case where the structural flowpaths are hydraulically continuous across the upper contact of the Calico Hills unit, water would be more likely to flow downward without a significant change in its path until it reaches the water table. In cases where the structural flow paths are discontinuous across the upper contact, flow may be diverted downdip along this boundary. Intermediate conditions between the two extreme cases are also possible. Recent numerical modeling (LBL96, ROB96) of flow through the unsaturated zone has provided important insights into the possible characteristics of flow in each subunit of the unsaturated zone. Some of these insights are discussed in the following paragraphs.

Discussion of Unsaturated Zone Conceptual Flow Model and Modeling of the Unsaturated Zone

Under current conceptualizations the net infiltration rate through the unsaturated zone beneath Yucca Mountain is one of the most critical parameters for determining the nature of flow in the unsaturated zone, yet it is one of the least well characterized. Numerous modeling studies, based on varying conceptual models, have been performed to simulate unsaturated flow beneath Yucca Mountain (e.g., DOE94a, DOE95b, LBL96, ROB96). Sensitivity analyses performed in these studies indicate that uncertainty in the amount of net infiltration accounts for as much as 90 percent of the variability in the results.

The magnitude of infiltration flux has a significant bearing on the potential for lateral unsaturated flow beneath Yucca Mountain. In the Paintbrush nonwelded unit, the overall hydraulic conductivity parallel to bedding is 10 to 100 times greater than that in the direction normal to the bedding plane. At higher flux rates, the potential vertical flow rate of some units is exceeded, thereby inducing a significant lateral component of flow to the infiltration flux. Some authors have examined the possibility of "focused recharge," a phenomenon in which surface rainfall runoff is directed to areas where faults intersect the surface. Significant amounts of recharge may infiltrate into these zones, which may induce lateral unsaturated flow in the underlying units (LEH92). One obvious area where this may be occurring is the northern extension of Solitario Canyon fault, which bounds Yucca Mountain on the west. As previously described, lateral flow could direct water to structural flow paths, which may then redirect the flow vertically downward, providing a "fast path" and potentially reduced travel times to the saturated zone.

There is growing evidence to suggest episodic water flow at Yucca Mountain may take place along "fast paths" (LBL95, FAB96, LBL96). Data obtained from recent sampling conducted within the ESF tunnels drilled into Yucca Mountain provide compelling evidence that not only does flow occur along "fast paths," but that such flow is capable of moving considerable distances over a relatively short time frame. The amount of water which may be infiltrating by fast paths is obviously of critical importance to predicting repository performance. Samples taken in the ESF tunnel show elevated concentrations of some radionuclides, principally chlorine-36, as well as lesser amounts of tritium and technetium-99 (FAB96). Chlorine-36 is a radioactive isotope produced in the atmosphere and carried underground with percolating ground water. High concentrations of this isotope were added to meteoric water during a period of global fallout from atmospheric testing of nuclear devices, primarily in the 1950's. This "bomb-pulse" signal can be used to test for the presence of fast transport paths (FAB96).

Testing for bomb-pulse radionuclides was conducted by collecting and analyzing rock samples from the ESF. Systematic samples were collected every 200 m, and feature-based samples were collected whenever a structural feature such as the intersection of the tunnel with a fault, was recognized. The results of the testing indicate that most of the samples had ^{36}Cl ratios ranging from 400e-15 to 1300e-15. The analysis in LANL96 indicates that although many samples showed ^{36}Cl ratios above present day atmospheric levels, it is believed that they represent Pleistocene water which entered the system when the ^{36}Cl ratios of infiltrating water were higher than they are today. Samples with ^{36}Cl ratios above 1500e-15 were interpreted as containing a component of bomb pulse water, indicating that at least a small proportion of the water at those locations is less than 50 years old. Locations at which multiple samples showed indications of bomb-pulse ^{36}Cl ratios appear to be associated with the Bow Ridge fault zone, the Drill Hole Wash fault zone, and the Sundance fault zone (ROB96). The most significant result of the ^{36}Cl testing is that some water travels to the repository horizon in less than 50 years. It is important to recognize, however, that these results do not indicate that all water travels this quickly in the unsaturated zone. The ^{36}Cl data do not indicate what fraction of the water now in the unsaturated zone has traveled by fast paths, nor do they by themselves indicate the magnitude of infiltration fluxes. Age dating, numerical modeling, and other lines of evidence suggest that travel times for most of the unsaturated zone are on the order of thousands to tens of thousands of years (LBL96).

Recent numerical modeling studies (LBL96, LANL96, ROB96) suggest two important requirements for rapid (less than 50 years) transport of ^{36}Cl to the ESF: 1) a continuous, high permeability pathway must exist to depth, and 2) a means of focusing infiltration and maintaining flux to the pathway must exist for a sufficient time. The eastward dip of the highly permeable PTn unit allowed strong lateral flow which was subsequently diverted downward at faults in these simulations. The strong lateral, down dip flow in the PTn was subsequently channeled into local permeability highs. In both the Paintbrush and Calico Hills units several vertical “fast paths” developed in response to these conditions. The recent modeling suggests that where the PTn is relatively thick, it was necessary to modify fracture properties to represent greater fracture densities and/or fracture apertures in order for bomb-pulse ^{36}Cl to migrate to the ESF in less than 50 years (ROB96).

The presence of perched water has implications for travel times, flow paths, and fluxes of water through the unsaturated zone. Analysis of water from several perched water zones documents a number of important findings, including perched water compositions that are out of equilibrium with pore water, showing little fracture/matrix interaction (DOE96d). This indicates that the perched water probably reached its present location without extensive travel through and interaction with the rock matrix, thus suggesting that this water had traveled relatively quickly through the unsaturated zone. Recently-measured tritium concentrations in perched water are at background levels, therefore suggesting that perched water is older than thermonuclear weapons testing. Also, preliminary data from isotope testing of perched water samples from boreholes

UZ-14 and SD-7 indicates an apparent residence time of about 10,800 years, with corrected ages ranging from 5,000 to 10,800 years (LBL96). A detailed conceptual model of perched water is presented in LBL96.

Radionuclide Transport in the Unsaturated Zone

The travel time of radionuclides beneath Yucca Mountain is a function of both physical and chemical processes and interactions between fluid and rock. In terms of physical processes, radionuclides travel by gas phase and liquid phase advection, dispersion, and diffusion. Radionuclide travel times to the accessible environment are a function of the percolation flux distribution in the unsaturated zone and the advective flux distribution in the saturated zone, as well as the hydrostratigraphy along the ground-water flow paths between the repository and the accessible environment. The percolation flux distribution within the Topopah Spring hydrostratigraphic unit (and other unsaturated zone units below it) is a function of the infiltration rate and the complex mechanism of ground-water flow in the unsaturated zone. Chemical influences on radionuclide travel times include retardation processes involving liquid and gas phase diffusion, ion-exchange, adsorption on solids, surface complexation, colloidal suspension, chemical reactions, mineral alteration and dehydration reactions, radioactive decay, and precipitation/dissolution reactions.

In particular, the key conceptual uncertainty in the transport of radionuclides through the unsaturated zone at Yucca Mountain is the presence of fracture flow and transport which might, if fracture pathways are continuous and interconnected, lead to the formation of "fast paths" to the underlying saturated zone.

Uncertainties in chemical retardation mechanisms and the lack of rock/radionuclide interaction data also lead to considerable uncertainty in predicting future repository performance. For instance, in TSPA (DOE95b), modeling efforts have simulated fluid/rock interactions that can serve to chemically retard the transport of radionuclides with a simple equilibrium (infinite capacity) distribution coefficient (K_d) model. Generally, values for distribution coefficients are related to both the chemical nature of the individual hydrostratigraphic unit and to the properties of the radionuclide. Since distribution coefficients are used to model such a wide variety of phenomenological processes, they are modeled in TSPA-95 as stochastic parameters with a high degree of uncertainty. This process results in a broad range of predicted times it would take radionuclides to travel from the repository to the water table. Radionuclides that are little affected by chemical retardation (e.g., I, Tc) could reach the water table within the same time frame as the ground water. Alternatively, K_ds used in TSPA-95 for a number of radionuclides (i.e., Am, Ra, Cs, Sr) result in travel times to the water table that are 50,000 times greater than those for the ground water. Plutonium exhibits significant sorption on all types of Yucca Mountain tuffs, with sorption coefficients often in excess of 100 cubic centimeters per gram (cc/g) (ROB96). Detailed analysis of laboratory data for ^{237}Np showed that a nominal sorption coefficient of 2.5 cc/g could be used in the clinoptilolite-rich zeolitic rocks, with a value of 0 cc/g elsewhere. Measured K_d values for ^{79}Se are on the order of one cc/g. Sorption of uranium, similar to ^{237}Np, is significant only for zeolitic tuffs (ROB96).

Recent numerical modeling of the role of rapid transport through fractures was studied for ^{237}Np (ROB96). For peak dose criteria, the model indicates that the peak may be a result of rapid radionuclide transport through fractures. However, this does not mean that most of the radionuclides travel through fractures. According to this model, 10 percent of the source radionuclides typically travel rapidly in the fracture system, while 90 percent traveled much slower in the matrix material. (Other conceptualizations suggest that up to 95 percent of flow is in the fractures.) These results must be interpreted with the realization that the distribution of the simulated flux between the fractures and matrix is entirely the result of the parameters used to characterize the system. The Calico Hills, the primary unit through which radionuclides must travel to get to the water table, is poorly characterized; nothing is known of its fracture hydraulic properties.

Simulations of ^{36}Cl ratios and ^{14}C in the unsaturated zone indicate that infiltration rates between one and five mm/yr are more consistent with the field measurements than infiltration rates on the order of 0.1 mm/yr (ROB96). The environmental isotope simulations also helped provide a reasonable explanation for the bomb-pulse ^{36}Cl ratios measured in the ESF. This explanation involves disturbance of the PTn (e.g., faulting) which led to increased bulk fracture permeabilities and provided a local hydrologic environment conducive to rapid fracture flow of a small fraction of the total infiltrating flux. The flow in the fractures associated with these disturbances is rapid enough to transport solutes from the ground surface to the ESF in less than 50 years.

When flow and transport in fractures is simulated using a particle tracking method, a bimodal distribution of travel times is obtained — an early arrival through fractures, followed by a much delayed breakthrough of radionuclides that traveled through the matrix (ROB96). Although ROB96 predicts that the percentage of the total radionuclide inventory that travels rapidly to the water table is small, the radionuclide flux entering the saturated zone is at its greatest level during this period, and thus the peak dose is controlled by fracture transport. Migration of radionuclides through fractures is likely to be retarded by diffusion and in some cases adsorption. ROB96 noted that there is an inverse relationship between infiltration rate and arrival time of first breakthrough peak.

Due to sparse data and limited or nonexistent testing of the CHn, characterization of fracture hydrologic properties in this unit is based on speculation and application of theoretical relationships (ROB96). Model simulations indicate that the nature of fracture flow in the Calico Hills is critical to characterizing the performance of the site. Changes in estimated hydrologic property values estimated for these units have considerably altered the simulated flow and transport behavior through the unsaturated zone natural barrier.

7.1.2.2 Hydrologic Characteristics of Saturated Zone Units

In contrast to the unsaturated zone in which the flow of water is considered to be primarily vertical, ground-water flow in the saturated zone at Yucca Mountain is principally in the horizontal direction. This consideration, coupled with the fact that it is the saturated zone in which most downgradient radionuclide transport from a repository would occur, requires the description of saturated zone hydrology to cover an area much greater than Yucca Mountain itself. Thus, while the discussion of unsaturated zone hydrology is conveniently limited to the Tertiary volcanic rocks beneath the proposed repository, this section broadens in scope to include not only the saturated volcanic rocks, but also the adjacent Paleozoic carbonates and the alluvial basin fill deposits. Because of the complex three-dimensional geometric relationships of these geologic materials, the BID breaks the description of saturated zone hydrology into two parts. Section 7.1.2.2 is restricted to a description of each of the three individual geologic materials (volcanic rocks, alluvium, and Paleozoic carbonates) and their hydrogeologic properties; Section 7.1.2.3 attempts to describe the geometric and hydrologic relationships of the various units to one another and to present an integrated picture of regional ground-water flow.

Before beginning a detailed description of the hydrologic properties of the individual aquifer units, it will be helpful for the reader to keep in mind the following information while reading this section. As previously described, Yucca Mountain is composed of a thick sequence of Tertiary volcanic rocks. Beneath Yucca Mountain, the thickness of these rocks is more than 1,800 m (SPE89). The Tertiary volcanic sequence is underlain by complexly folded and faulted

Paleozoic sedimentary rocks, including thick sections of carbonate rocks (SPE89). The Paleozoic rocks beneath the volcanic section are water-saturated and capable of transmitting ground water, probably over great distances. Bounding Yucca Mountain on three sides are downdropped basins filled with alluvial deposits eroded from the surrounding mountains. Water recharged in the higher altitude areas north of Yucca Mountain flows generally southward through the volcanic, carbonate, and alluvial aquifers toward discharge areas located in the southern Amargosa Desert and in Death Valley.

Volcanic Aquifer

At Yucca Mountain, where the volcanic rocks may or may not be fractured and where the hydrologic properties can change significantly in a single stratigraphic unit, stratigraphic units are useful only in a very general sense for defining hydrogeologic units. The volcanic rock section beneath Yucca Mountain has been divided informally into the four hydrogeologic units shown in Figure 7-21: 1) the upper volcanic rock aquifer, 2) the upper volcanic confining unit, 3) the lower volcanic aquifer, and 4) the lower volcanic rock confining unit. Note that the boundaries of these hydrogeologic units do not correspond necessarily to stratigraphic or thermal/mechanical units as defined by other studies. Ground water flows through all of these units to some degree (where saturated); these hydrogeologic unit designations serve primarily to distinguish between zones which transmit relatively large quantities of ground water (“aquifers”) and zones which transmit lesser, but not necessarily insignificant, amounts of ground water (“confining units”) (DOE95e; USG94a).

The largely nonwelded and intensely altered lower volcanic section, the Lithic Ridge Tuff and older tuffs, is a confining unit. The variably-welded Crater Flat Tuff constitutes an aquifer of moderate yield. The tuffaceous beds of Calico Hills are largely nonwelded and are zeolitized where saturated; however, this unit is significantly less altered than the lower volcanic section. Where saturated, it is generally a confining unit, but locally parts of the formation are permeable.

The Topopah Spring Member of the Paintbrush Tuff is predominantly densely welded and has abundant lithophysal horizons. It contains the zones of greatest primary and secondary permeability and constitutes the most productive aquifer in the tuff section, where it is saturated (FRI94). Units of the lower volcanic aquifer generally are completely or mostly in the saturated zone. Because it is deeper, increased lithostatic load probably accounts for part of the difference between the two aquifers, but the lower aquifer also tends to be less fractured than the upper

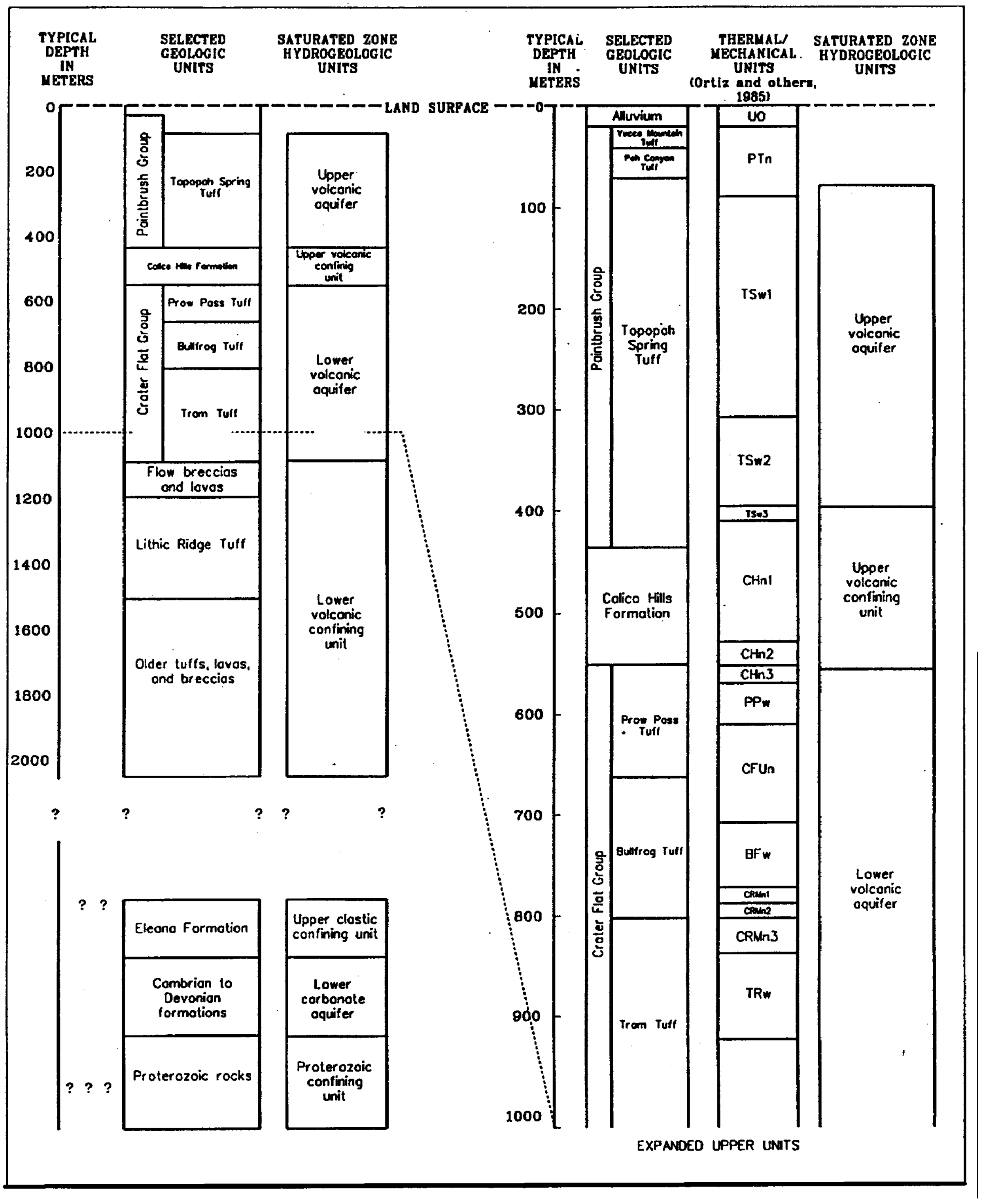


Figure 7-21. Saturated Zone Hydrostratigraphy of Volcanic Rocks (USG96a)

volcanic aquifer. The lower volcanic aquifer is also more altered, which accounts for the decreased permeability (USG96a).

The physical properties within each formation vary considerably, largely due to variation in the degree of welding of the tuffs. The nonwelded tuffs are characterized by having a relatively large primary porosity, but low permeability. This low permeability results from small pore sizes and the presence in many nonwelded units of secondary alteration minerals (primarily zeolites and clays). The welded tuffs are typically very hard and densely welded. The welded tuffs are commonly more highly fractured than the nonwelded units. The fractures in the welded tuffs endow them with a significant bulk permeability. For this reason, many of the welded tuff units are capable of transmitting greater quantities of water than their nonwelded counterparts (USG84a).

The occurrence of the water table is not restricted to any one hydrogeologic unit. Directly beneath Yucca Mountain, the water table occurs primarily within the Calico Hills Formation and toward the southern end of Yucca Mountain in the underlying Crater Flat Tuff. To the east of Yucca Mountain, in the vicinity of Forty Mile Wash, the water table occurs in the Topopah Spring member of the Paintbrush Tuff. The occurrence of the water table in different hydrostratigraphic units is attributable to three factors: 1) the vertical displacement of hydrostratigraphic units by the numerous faults that dissect the area, 2) the eastward dip (five to 10 degrees) of the volcanic units, and 3) the variable elevation of the water table. See USG93a and USG84b for graphical depictions of the relationship of the water table to stratigraphic units and FRI94 for a map of the geology at the water table.

Aquifer Geometry

The thickness of the volcanic units is greatest to the north of Yucca Mountain toward the eruptive centers of the Timber Mountain Caldera Complex (USG85a; USG90a), diminishing gradually from the eruptive centers to zero thickness at the limits of the southwest Nevada volcanic field. The thickness of the volcanic deposits also varies considerably for two reasons. First, these units were deposited on a topographic surface of considerable relief. Second, erosion and postdepositional structural events have significantly modified their original distribution and thickness (USG85a, p. 8). In the vicinity of Yucca Mountain, the only direct measurement of the thickness of the volcanic sequence has been at Well UE-25p#1, where the thickness was measured to be 1,244 m. Seismic reflection studies have not yielded definitive data, owing to absorption of reflected energy by the thick volcanic cover (USG85a). Drill hole USW H-1, located immediately north of the proposed repository boundary, was drilled to a depth of 1,829 m entirely in volcanic rocks. Thus, the thickness of the volcanic sequence at the north end of Yucca Mountain may exceed 2,000 m.

The saturated thickness of the volcanic unit has been measured only at Well UE-25p#1. At this location, the water table is 752.6 m above mean sea level (MSL) and the bottom of the volcanic sequence was encountered at 129.1 m below MSL, giving a saturated thickness of the volcanic rocks of approximately 881.7 m (USG84c). Other information can be used to provide a crude approximation of the saturated thickness of the volcanic units. For example, the elevation of the water table beneath Yucca Mountain ranges from 1029 m above MSL at the northern part of Yucca Mountain to 729 m above MSL at the southern end of Yucca Mountain, a difference of 300 m (USG94a). Assuming that the bottom of the volcanic sequence beneath Yucca Mountain is 129 m below sea level everywhere (which it assuredly is not), the saturated thickness of the volcanic sequence would range from about 1,158 to 858 m.

The subsurface extent of the volcanic units south of Yucca Mountain is not reliably known because the volcanic rocks dip under and are covered by alluvial deposits of the Amargosa Desert. See Figure 7-15 for an illustration of the generalized extent of the volcanic rocks in southern Nevada and Figure 7-22 for a schematic cross-section showing the southward thinning of the volcanic units. Aeromagnetic maps suggest that the volcanic rocks pinch out at about the latitude of Lathrop Wells, and therefore, alluvial deposits constitute most or all of the cover in the Amargosa Desert (USG85a). Further evidence for the disappearance of the volcanic rocks is provided by two oil exploration wells drilled in the Amargosa Valley (DRI94). These two wells were drilled through alluvium into the underlying carbonate aquifer without encountering any volcanic rocks. USG85a, p. 12, notes that the “southward thinning of the volcanic rocks has been placed in question by recent north-south unreversed seismic refraction measurements. Preliminary profiles suggest that some highly magnetized volcanic rocks may indeed thin as proposed but that an underlying rock sequence of less magnetized volcanic rocks may continue southward far beyond Lathrop Wells.” USG91a notes the presence of rhyolitic volcanic units

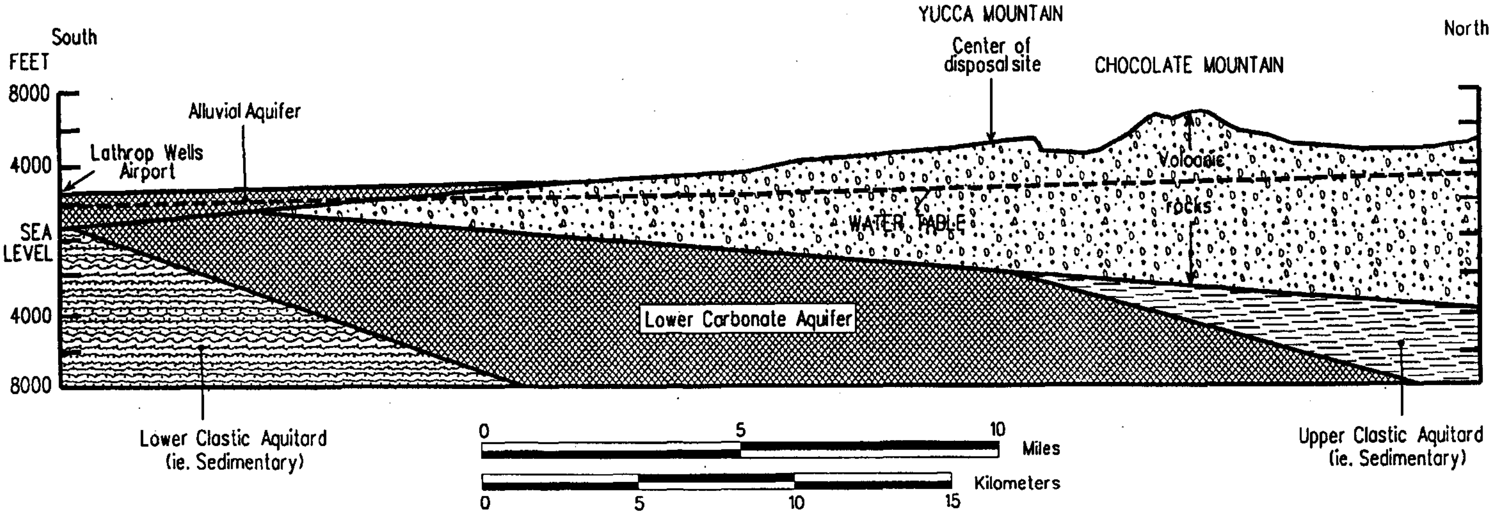


Figure 7-22. Schematic North/south Cross-sectional Illustration of Thinning of Volcanic Units Beneath the Amargosa Desert (USG85a)

within the Amargosa Basin, although the genetic relationship of these units, if any, to the volcanic rocks that comprise Yucca Mountain is not clear.

Bare Mountain, located approximately nine kilometers to the west of Yucca Mountain across Crater Flat, consists of Paleozoic rocks. Tertiary volcanic rocks are known to lie beneath the area may be located at the eastern bounding fault of Bare Mountain. To the north and east of Yucca Mountain, the volcanic sequence continues for several to several tens of kilometers.

Hydraulic Conductivity

Rock properties largely control the characteristics of water occurrence and flow in the saturated zone. Rock properties, in turn, are dependent on eruptive history, cooling history, post-depositional mineralogic changes, and structural setting. Permeability of ash-flow tuffs is in part a function of the degree of fracturing, and thus, the degree of welding. Densely-welded tuffs fracture readily; airfall tuffs do not. Therefore, the distribution of permeability is affected by irregular distribution of different tuff lithologies and is a function of proximity to various eruptive centers. Permeability is also a function of proximity to faults and fracture zones (USG82a).

The most reliable method for determining aquifer hydraulic properties are pumping tests, especially those in which drawdowns are measured and analyzed in wells other than those being pumped. More than 150 individual aquifer tests have been conducted at and around Yucca Mountain since the 1980s. Most hydraulic data were from tests conducted in the lower volcanic aquifer and in the lower volcanic confining unit. Very few data were available for the upper confining aquifer and the upper volcanic confining unit. Almost all the tests were single-borehole tests in specific depth intervals and included constant-discharge, fluid-injection, pressure-injection, borehole flow meter, and radioactive tracer tests. Multiple-borehole tests have been conducted only at the C-well complex (USG96b, DOE96a). Most reported values of hydraulic conductivity available in the published literature were calculated from transmissivity values calculated from single-borehole pumping tests and should be regarded as “apparent hydraulic conductivity.” Single-borehole tests do not record drawdown data from a large enough sample of the aquifer to be considered reliable. Drawdown data in the pumped well may be affected by a variety of factors such as fractures, well efficiency, borehole storage, gravity drainage, and borehole plumbing. USG96b reported that transmissivity and apparent hydraulic conductivity values determined using multiple-borehole hydraulic tests tend to be much higher—about two orders of magnitude—than values reported for single-borehole tests conducted at the same borehole.

Laboratory permeameter testing has been conducted on core samples taken during drilling of boreholes at Yucca Mountain. Welded units were reported to have matrix hydraulic conductivities with geometric means ranging from $2.0x10^{-6}$ to $3.0x10^{-6}$ m/day and bulk hydraulic conductivities of 0.09 to 10.1 m/day. The nonwelded units have variable hydraulic conductivities, with geometric means ranging from $2.6x10^{-5}$ to $3.0x10^{-2}$ m/day (USG84a).

USG91b reports that, for Well USW H-6, water production during pumping tests was coincident with fractured, partially, and partially- to moderately-welded tuff units. The reverse was not necessarily true; that is, not all fractured partially-welded tuff units produced water. USG91b also states that for Well USW H-6 "porosity and permeability of these rocks is generally inversely related. Porosity is greatest near the top and bottom of ash flow tuff units and is the least near the center. Permeability, as indicated by water production, is greatest near the center of units, where the degree of welding is greatest."

Hydraulic conductivity of the Topopah Spring Member, as determined from aquifer testing of a 120 meter interval of Well J-13, located about five miles east of the crest of Yucca Mountain, is about one m/d. Below the Topopah Spring Tuff Member, tuff units are confining beds. Hydraulic conductivities of units tested below the Topopah Spring Member at Well J-13 range from 0.0026 to 0.15 m/d (USG83).

Beneath Yucca Mountain, the Topopah Spring Member is above the water table. Wells installed in Yucca Mountain are open to the upper volcanic aquitard (Calico Hills Formation) and the lower volcanic aquifer (Crater Flat Tuff). Pumping tests conducted in these wells derived water primarily from the Bullfrog and Tram Members of the Crater Flat Tuff (USG91b). Hydraulic conductivities calculated from single-borehole pumping test data are shown in Table 7-5.

Table 7-5. Hydraulic Conductivities Calculated from Pumping Test Data

Well	K (m/day)	Source
UE-25b#1	0.46	USG84d
USW H-4	0.3 - 1.1	USG85c
USW H-6	0.85	USG91b
USW G-4	1.34	USG86

In addition to the cautions expressed above regarding the accuracy of single-borehole pumping test analyses, it is important to recognize that the values of hydraulic conductivity presented here are average values for the entire pumped interval in the well. Borehole flow surveys, in conjunction with acoustic televiewer logging, indicate that the volcanic rocks are highly inhomogeneous in the vertical direction and that the majority of water yielded from the wells derives from a few highly fractured water-bearing zones of limited thickness. The hydraulic conductivities shown above are likely to significantly underestimate the actual horizontal hydraulic conductivity of the water-bearing zones and to overestimate the hydraulic conductivity of the less transmissive zones. USG91b estimates hydraulic conductivities for specific intervals within the volcanic section. The authors calculated a hydraulic conductivity of about 9.1 m/d for a 15.2-meter section of the Bullfrog Member and 6.7 m/d for a 10.4-meter section of the Tram Member.

As previously stated, multiple-borehole tests have been conducted only at the C-well complex (USG96b, DOE96a). The pumping tests at this location involved pumping of selected horizons isolated by inflatable packers. In this way, transmissivity and hydraulic conductivities can be calculated for individual members of an aquifer or confining unit. The following description of transmissivity and hydraulic conductivity data is taken directly from DOE96a.

The results of four pumping tests conducted from June 1995 to May 1996 indicate that the transmissivity of the Calico Hills interval typically is 100-200 ft^2/d; the transmissivity of the Prow Pass interval typically is 400-700 ft^2/d; the transmissivity of the Upper Bullfrog interval typically is 400-1,000 ft^2/d; and the transmissivity of the Lower Bullfrog interval typically is 18,000-20,000 ft^2/d. The pumping tests conducted in 1996 indicate that transmissivity is about the same from UE-25 c#1 to UE-25 c#3 as it is from UE-25 c#2 to UE-25 c#1 (DOE96a). Horizontal hydraulic conductivities were calculated from computed transmissivities by dividing the transmissivity by the thickness of the transmissive rocks in the interval. Horizontal hydraulic conductivity typically is one to five ft/d in the Calico Hills interval and five to 10 ft/d in the Prow Pass interval. The horizontal hydraulic conductivity of the Upper Bullfrog interval typically is two to three ft/d from UE-25 c#1 to UE-25 c#3 and eight to 10 ft/d from UE-25 c#2 to UE-25 c#3. The horizontal hydraulic conductivity of the Lower Bullfrog interval typically is 70-90 ft/d from UE-25 c#1 to UE-25 c#3 and 150-210 ft/d from UE-25 c#2 to UE-25 c#3. Composite horizontal hydraulic conductivity from UE-25 c#2 to UE-25 c#3 consistently was found to be twice the composite value from UE-25 c#1 to UE-25 c#3. Ratios of vertical to horizontal hydraulic conductivity were determined to range downward from 0.08 to 0.0008 in the Calico

Hills, Prow Pass, and Upper Bullfrog intervals. Note that the anisotropy in calculated hydraulic conductivities between UE-25 c#2/#3 and UE-25 c#1/#3 is opposite of that predicted on the basis of prevalent fracture orientations. The layout of the three boreholes to form a triangular pattern, with boreholes UE-25 c#1/#3 located along a line estimated to be the major semiaxis of the permeability tensor and UE-25 c#2/#3 along a line estimated to be the minor semiaxis of the permeability tensor (USG96a, p. 48). One possible explanation for this can be found in the relative distances of the wells from each other. Well #1 is twice the distance from #3 (pumped well) than is well #2; the apparent anisotropy may result from fracture/channeling effects associated with sampling the aquifer at different scales.

Porosity

In terms of bulk porosity, the volcanic sequence may be considered to consist of two different types of tuffs: welded and nonwelded (or bedded). The welding process generally reduces the matrix porosity. Therefore, the welded tuffs typically have a lower porosity than the non-welded tuffs (USG75, USG84a). The welded tuffs are also more highly fractured than their nonwelded counterparts. USG84a reports that welded units have a mean fracture density of eight to 40 fractures per cubic meter and mean matrix porosities of 12 to 23 percent. The nonwelded units have a mean fracture density of one to three fractures per cubic meter and mean matrix porosities of 31 to 46 percent. In both rock types, however, matrix porosity probably comprises the majority of bulk porosity because fracture porosities, even in the more highly fractured units, are reportedly quite small (USG85d). USG85d, using a theoretical model to calculate fracture porosity, reports a fracture porosity of tuffs penetrated by Well USW H-4 ranging from 0.01 to 0.1 percent. Matrix porosities probably decrease with depth due primarily to lithostatic loading and formation of secondary minerals (SPE89).

Effective Porosity

Effective porosity is that portion of the total porosity that contributes to saturated flow. Many of the volcanic rocks are characterized by relatively small pore sizes and lack of inter-connectedness of pores; thus, the effective porosity is normally significantly less than the total porosity. USG84a, p. 18, reports that preliminary laboratory studies of the vitric facies of the Calico Hills unit show that only about five percent of the pore space is large enough to contribute significantly to flow under saturated conditions. USG85d, p. 28, considers that fracture porosity is a reasonable estimate of effective porosity. USG83, p.13, reports that effective porosities in samples of welded tuff, vitrophyre, and zeolitized clayey pumiceous tuff range from 2.7 to 8.7 percent.

Storage Properties

Numerous pumping tests have been conducted in water wells completed in the volcanic rocks at Yucca Mountain and may be used to estimate storage properties. However, most calculations of storage coefficients for the volcanic rocks are based on single well pumping tests which generally do not produce reliable estimates of storage properties. The ground-water storage characteristics of the fractured tuffs at Yucca Mountain are complex (USG85d). Estimates of storage properties of the volcanic rocks vary widely, depending partly upon the lithology and the degree of hydraulic confinement of the unit being tested. A particular hydrostratigraphic unit may be under unconfined conditions at one location and under confined conditions at another. USG91b calculates a storage coefficient of about 0.2. USG93a, p. 78, calculated storage coefficients for the more densely welded units that ranged from $1x10^{-5}$ to $6x10^{-5}$; for nonwelded to partially-welded ash flow tuff zones storage coefficients were estimated to range from $4x10^{-5}$ to $2x10^{-4}$. Composite storage coefficients calculated from the multiple-borehole C-well tests ranged from 0.001 to 0.004 (DOE96a).

The degree of confinement of the volcanic aquifers and confining units varies in ways that are consistent with the geology of the intervals and their distance below the top of the saturated zone (USG96b, DOE 96a). Beneath Yucca Mountain, the water table is within or just above the Calico Hills interval (upper volcanic confining unit); this interval typically responds to pumping as an anisotropic, unconfined aquifer. The underlying Prow Pass and Upper Bullfrog intervals (part of the lower volcanic aquifer) respond to pumping as either a leaky, unconfined or fissure-block aquifer. The Lower Bullfrog, isolated by intervals of nonfractured rock, typically responds to pumping as a nonleaky, confined aquifer.

Recharge and Discharge

Precipitation is the primary source of recharge to the volcanic aquifer (USG86; USG83). Snowmelt in the Timber Mountain area to the north of Yucca Mountain, as well as on Yucca Mountain itself, provides some of the precipitation-derived recharge. The occasional intense rainstorms experienced in the area also provide a source of recharge to ground water. However, because so much of the water that falls either evaporates immediately or is directed into steep channels along the flanks of the mountains to the permeable talus and alluvial deposits at the base of the mountain, the extent of this contribution is less certain.

Various methods have been employed to estimate the amount of precipitation that recharges the saturated zone beneath Yucca Mountain (NDC70; USG84e; USG82b). The most frequently employed approach is to divide the recharge area into a number of zones by altitude and to assume higher precipitation at the higher altitude zones. Some fraction of this precipitation, usually less than 10 percent, is then assumed to recharge the underlying saturated zone. Enhancements of this method allow for variable infiltration fractions to account for factors such as topography, rock type, and vegetation. In the volcanic system, recharge is more easily quantified than discharge, and discharge is usually calculated by assuming that outflows are equal to inflows. This assumption is necessary, but questionable. Some researchers have raised the possibility that the volcanic aquifer may still be equilibrating to a long term pulse of higher recharge during the wetter climate of the Pleistocene (about 10,000 years ago) (USG85f, USG96a). This possibility is not inconsistent with apparent ground-water ages of 9,000 to 15,000 years calculated for the volcanic aquifer (USG93a; USG83). NDC70 estimated that the maximum recharge for Crater Flat and Jackass Flats is three percent of the precipitation rate, or about 4.5 mm/y. USG84a considers this the upper bound for the recharge rate that may be occurring in certain parts of the saturated zone beneath Yucca Mountain, estimating that recharge ranges from approximately 0.5 to 4.5 mm/year. Recent evidence, discussed previously, indicates that the percolation flux through the unsaturated zone probably ranges from one to 10 mm/yr, and averages approximately five mm/yr. Most of this percolation flux would be expected to recharge the saturated zone.

An upward hydraulic gradient from the underlying Paleozoic carbonate unit to the volcanic units (measured in Well UE-25p#1) indicates the potential for flow in the carbonate rocks to move into the overlying volcanic units. Additional evidence of upwelling flow from the carbonate aquifer includes zones of elevated ground-water temperature and carbon isotopic relationships. Elevated temperature measurements from the upper saturated zone indicate the possibility of upwelling from the carbonate aquifer along the Solitario Canyon fault and in the area between the Bow Ridge and Paintbrush Canyon faults (USG96a, FRI94). Stuckless et al. (STU91) used the relationship of the $^{13}C/^{12}C$ ratio to the $\delta^{14}C$ of the ground water to argue for at least three sources of water under the mountain. They tentatively identified the three sources as: 1) lateral flow from the tuff aquifer to the north; 2) local recharge, probably introduced dominantly by flow in flash-flood watercourses on the eastern side of Yucca Mountain (Forty Mile Wash); and 3) water that upwells from the deep carbonate aquifer into the tuff aquifer. Savard (SAV94) has documented recharge to the volcanic aquifer from intermittent streamflow in Forty Mile Wash. In a saturated zone ground-water model developed by the USGS, areal recharge had to be specified along Forty Mile Wash for the model to adequately simulate measured potentiometric levels in the vicinity of Yucca Mountain (USG84e).

Potential pathways by which ground water leaves the volcanic units include downgradient outflow, pumping, outflow to the carbonate aquifer, and flow into the unsaturated zone. Of the four pathways, flow into the unsaturated zone, where it occurs, is probably among the least significant (USG96a). There is no direct evidence that water from the volcanic units flows into the carbonate aquifer. Vertical hydraulic gradients, where measured, indicate the potential for flow is from the carbonate aquifer to the volcanic aquifer. The DOE states that the “current conceptual model for the regional ground-water flow system considers that ground water in the volcanic rocks beneath Yucca Mountain moves generally southward and discharges in the subsurface into the valley fill alluvium as the volcanic section thins and ultimately pinches out south of Yucca Mountain” (DOE95f). Currently, water is pumped from the volcanic aquifer from two wells, J-12 and J-13, located in Jackass Flat near Forty Mile Wash. These wells supply water for part of the Nevada Test Site, as well as for all site characterization activities at Yucca Mountain, including human consumption.

Paleozoic Carbonate Aquifer

Thick sequences of carbonate rock form a complex regional aquifer system or systems that are largely undeveloped and not yet fully understood. Secondary permeability in this sequence has developed as a result of fracturing and enlargement of existing fractures by solution. The area underlain by carbonate rocks is characterized by relatively low volumes of runoff. Flow can be complex and may include substantial interaction with volcanic and basin fill aquifers (USG75).

Due to the extensive, thick cover of volcanic rocks and alluvium in the vicinity of Yucca Mountain, the local characteristics of the Paleozoic sequence are not well known. In eastern Nevada, the Paleozoic sequence of sedimentary rocks is commonly divided into four general hydrogeologic units: the lower clastic aquitard, the lower carbonate aquifer, the upper clastic aquitard, and the upper carbonate aquifer. Evidence from drill hole data and geologic mapping in surrounding mountain ranges indicates that only the lower carbonate aquifer may be present in the vicinity of Yucca Mountain and to the south.

Aquifer Geometry

Evidence suggests that the lower Carbonate aquifer underlies the entire area. Exposures of Paleozoic rocks at the perimeter of the study area include Bare Mountain to the west of Yucca Mountain, the Funeral Mountains south of the Amargosa Desert, and the Specter Range to the east and southeast. Further evidence comes from three drill holes which have penetrated the overlying units to reach saturated carbonate rocks — borehole UE-25p#1 on the eastern flank of Yucca Mountain, which penetrated through Tertiary volcanic rocks into the underlying carbonate sequence, and two oil wildcat wells drilled near Amargosa Valley. Additional information regarding these wells is provided in Table 7-6.

Examination of the altitudes of the top of the carbonate aquifer in Table 7-6 indicates that the buried surface of the buried carbonate aquifer is quite irregular. This variability is probably a combination of relief of the original erosional surface of the carbonate units coupled with structural offsets produced by faulting.

Table 7-6. Borehole Location and Depth Data for Wells Drilled to the Lower Carbonate Aquifer in the Vicinity of and Downgradient of the Yucca Mountain Area

Well ID*	Latitude & Longitude	Surface Altitude (m)	Depth to Carbonate Aquifer (m)	Altitude (MSL) of Top of Carbonate Aquifer (m)
UE-25 p#1	36°49′38″/ 116°25′21″	1,114.9	1,244	-129.1
Federal-Federhoff 5-1	36°35′32″/ 116°22′54″	772.9	259	513.9
Federal-Federhoff 25-1	36°37′07″/ 116°24′26″	783.9	671	112.9

*Note: Information for well UE-25 p#1 obtained from USG84c. Information on oil exploration wells obtained from DRI94.

Saturated thickness of this aquifer is largely unknown; USG75 indicates that water circulates freely to depths of at least 1,500 feet beneath the top of the aquifer and up to 4,200 feet below land surface. The effective flow thickness of the aquifer depends, in part, upon the lithostatic pressure at depth, which in turn depends on the thickness of the column of rock overlying the carbonate aquifer.

Hydraulic Conductivity

Interstitial permeability of the carbonate rocks is negligible; essentially all of the flow transmitted through these rocks is through fractures. Permeability measurements of the carbonate rocks are reported as transmissivity values, as opposed to hydraulic conductivity values, because the thickness of the carbonate unit through which water is flowing is not well known. Estimates of fracture transmissivity range from 1,000 to 900,000 gallons per day per foot (USG75). USG75 reports the results of six pumping tests in the lower carbonate aquifer. The average calculated transmissivity was 13,000 gallons per day per foot.

Porosity

USG75 reports that total porosity determinations were made for 16 samples of the lower carbonate rocks. Total porosities ranged from 0.4 to 12.4 percent with an average of 5.4 percent. Fracture porosity of the rock is estimated to range from 0 to 12 percent of rock volume.

Effective Porosity

Due to the extremely low matrix permeability of the carbonate rocks, effective porosity can be approximated as the effective porosity of the fractures. Many of the fractures in the carbonate units are partially filled with clay or other materials which reduce both fracture permeability and effective porosity. USG75 reports that effective porosity values determined for 25 samples of the lower carbonate rocks ranged from 0.0 to 9.0 percent, with an average of 2.3 percent.

Storage Properties

USG75 reported that, based on examination of rock cores, the effective fracture porosity of the lower carbonate aquifer is probably a fraction of one percent; accordingly, the storage coefficient under unconfined conditions is not likely to exceed 0.01. Because of the extremely low effective porosity of the carbonate rocks, the specific storage under confined conditions probably ranges between 10^{-5} and 10^{-6} per foot. Where the aquifer is several thousand feet thick the storage coefficient may be as large as 10^{-3}.

Recharge and Discharge

Direct areal recharge to the carbonate aquifer occurs where these rocks are exposed at the surface. The highest amounts of areal recharge are expected to occur in highland areas where precipitation levels are highest and where the highly fractured rocks are exposed at the surface. Recharge to the carbonate units may also derive from downward infiltration through overlying volcanic or alluvial deposits. The relationship of flow potential in the carbonate aquifer to that in the overlying units is not well known. No downward gradients have been measured between the carbonate aquifer and overlying units in the study area. This would seem to indicate that the recharge areas for the carbonate aquifer are located relatively far away from Yucca Mountain. North of the proposed repository area is an area of relatively high hydraulic gradient, measured in the saturated volcanic rocks. One proposed explanation for this high hydraulic gradient is an inferred east-west striking graben which provides a conduit for ground water flowing in the volcanic aquifer to drain into the underlying carbonate aquifer (FRI94). If this is the case, then the carbonate aquifer is being recharged by flow from the overlying volcanic units at this location.

The only measurements of potential in the carbonate aquifer made near Yucca Mountain indicate vertically upward hydraulic gradients over wide areas of the carbonate unit. Over at least part of the study area (in borehole UE-25 p#1) and beyond (specifically in the Amargosa Desert east of the Gravity and Specter Range Faults), upward hydraulic gradients have been measured between the carbonate aquifer and overlying units. These upward hydraulic gradients indicate the potential for upward flow, but do not demonstrate that such flow is occurring in these areas. Discharge from the carbonate aquifer would occur in those areas where such flow actually occurs. FRI94 describes anomalously high ground-water temperatures measured beneath Yucca Mountain in the saturated volcanic aquifer which indicates upward flow (discharge) from the carbonate aquifer into the overlying volcanic units may be occurring in the vicinity of the Solitario Canyon Fault.

One major discharge location for flow in the regional carbonate aquifer is at Ash Meadows, located southeast of Yucca Mountain. It is not clear, however, whether discharge at Ash Meadows includes any ground water that has flowed beneath Yucca Mountain (this point is discussed in more detail in Section 7.1.2.3). Additionally, Death Valley, located about 60 kilometers south-southwest of Yucca Mountain, is regarded by many researchers as the base level or terminus for the entire regional system and, as such, accommodates discharge from the carbonate aquifer (USG88a). There are also numerous small, relatively low flow springs located throughout eastern Nevada, though to a lesser extent in the study area, which represent discharge points from the carbonate aquifer(s) (USG75).

Alluvial Aquifer

Valleys, topographic basins, and other topographic and structural lows are filled with variable thicknesses of unconsolidated, often poorly-sorted sand and gravel deposits. Lacustrine and eolian deposits are found locally. Basin-fill deposits are generally 2,000 to 5,000 feet thick, but in some basins exceed 10,000 feet in thickness. Basin-fill ground-water reservoirs are restricted in areal extent, generally being bounded on all sides by mountain ranges. Beneath the central parts of the deeper valleys, the water table is encountered in the alluvium. At and near the valley margins, the alluvium is relatively thin and the water table occurs in the underlying consolidated rocks.

In the Yucca Mountain area, several basin-fill aquifers or potential aquifers exist. These are: Crater Flats, west of Yucca Mountain; Jackass Flats, east of Yucca Mountain; and Amargosa Valley, located south of Yucca Mountain. The Amargosa Valley aquifer is substantially larger and more significant as an aquifer than the Crater Flats and Jackass Flats basins (USG91a). Farther to the south, across the Funeral Mountains, lies the Death Valley alluvial aquifer.

Aquifer Geometry

The intermontane alluvial basins tend to be elongated in a north-south direction and are of roughly the same dimensions as the mountain ranges that separate them (FIE86). The alluvial fill thickens toward the center of the basins. The Crater Flats and Jackass Flats alluvial basins are bounded on their northern sides by mountainous areas at approximately the latitude of the north end of Yucca Mountain. Crater Flat is bounded at its southern end by a small, southeast trending ridge of rock outcrops. Topographic map patterns and satellite photographs (DOE95g) suggest that the Crater Flat Basin may be closed. The Jackass Flats basin does not have a well-defined southern terminus; it appears to have an outlet at its southwestern end which merges into the larger, northwest trending Amargosa Desert Basin. The Amargosa Basin is bounded on its northwest end by the Bullfrog Hills and on its southwestern boundary by the Paleozoic carbonate sequences of the Funeral Mountains. Both the Crater Flats and Jackass Flats alluvial basins are bounded below by their contact with Tertiary volcanic rocks (USG88b; USG83). South of Yucca Mountain, the volcanic sequence thins and probably pinches out (USG85a). If so, alluvial deposits may rest directly on top of Paleozoic carbonate units in the southern part of the basin. As previously described, two oil exploration wells drilled in the Amargosa Desert, near the town of Amargosa Valley, went through sedimentary (mostly alluvial) deposits into the carbonate aquifer. The thickness of the alluvial deposits at these wells was 259 m and 671 m, respectively (See Table 7-6). The exact nature of the sediments through which these wells were drilled is not clear, as drilling logs were not examined. DRI94 refers to the sediments both as "alluvium" and as "Neogene." Czarnecki and Wilson (HST91, p. 22) refer to deep (600 m) boreholes in the south-central Amargosa Desert which terminated in "Tertiary basin-fill sediments" underlying the Quaternary alluvial fill, thus opening the possibility that the Quaternary alluvial basin-fill sediments do not directly overlie the Paleozoic carbonate sequence, but are instead separated from it by an unknown thickness of undifferentiated Tertiary sediments.

Thicknesses of the deposits in the three alluvial basins in the study area are not well known due to the scarcity of drill holes that penetrate the entire alluvial sequence. Two drill holes in Crater Flat (USW VH-1 and USW VH-2) penetrate through the alluvial cover into volcanic rocks. Thickness of the alluvium in drill hole USW VH-2 is approximately 305 m, with a depth to water of 164 m. In Jackass Flats, Well J-13 penetrated approximately 137 m of alluvium prior to entering Tertiary volcanic rocks; the alluvium was not saturated at this location (USG83). Most of the wells drilled in the Amargosa Valley are water wells for irrigation and water supply. Since most of these wells encountered sufficient water in the alluvium, drilling was not carried through to the underlying units; thus, direct evidence for the thickness of the Amargosa Basin alluvial deposits is lacking. Indirect evidence (geophysical methods) indicates that the thickness of the alluvial cover in the southern Amargosa Desert may be as much as 1,585 m (USG89).

Saturated thickness and depth to water varies considerably among basins and within a given basin. In basins where significant discharge areas exist (typically manifested as dry lakes or playas), depth to water may be only a fraction of a meter to a few meters. Other alluvial basins may have no saturated zone at all. In the Amargosa Basin, south of Yucca Mountain, the water table in some irrigation wells is about 56 m deep. Considering that the basin may be over 1500 m deep, the thickness of the saturated zone in the Amargosa Basin could be over 1500 m. A study conducted in the Amargosa Basin area (USG89) concluded that at least 85 percent of the alluvial thickness in the Amargosa Basin is saturated.

Hydraulic Conductivity

USG75 reports the results of several single well pumping tests in alluvial aquifers at the Nevada Test Site. These wells are located outside of the area studied for the Yucca Mountain Project, but the formations tested are broadly similar, and the results are generally applicable to alluvial deposits within the immediate area of concern. These authors found the hydraulic conductivity of the alluvial deposits to range from 0.020 to 2.84 m/d. Due to the discontinuous nature of individual lenses or units within alluvial fill, hydraulic conductivity is expected to show wide variations in magnitude.

Porosity

The sediments which comprise the alluvial fills are typically coarse grained and poorly sorted, most of them having been deposited by flash flood conditions over many thousands of years. Although sediments such as these characteristically have relatively large total porosities, measured porosities tend to be highly variable due to their poorly sorted nature. USG75 reports that the total interstitial porosity of 42 samples of valley fill range from 16 to 42 percent and averaged 31 percent. Caliche, where present, would reduce porosity, perhaps significantly. USG75, p. 37, reports that caliche is a common cementing material at all depths in a shaft sunk in alluvium in the northwestern part of Yucca Flat to a depth of 550 feet.

Effective Porosity

Poorly sorted sediments often have values of effective porosity that are substantially less than their total porosity. Given the grain size and poorly sorted nature of the alluvium, effective porosity values may range from a few percent to perhaps as much as 25 to 30 percent.

Storage Properties

NDC63 estimated specific yield for the alluvial deposits in the Amargosa Basin using grain size distribution methods. The estimated average specific yield for this basin is 17.34 percent; actual values ranged from not less than 10 percent to not greater than 20 percent (NDC63).

Recharge and Discharge

There are several potential sources of recharge for the alluvial aquifers in the vicinity of Yucca Mountain. One source is direct recharge from precipitation falling on the alluvial areas. Recharge is also derived to some extent from infiltration of intermittent surface waters of the Amargosa River and washes draining off the mountains (SAV94). A third source of recharge to alluvial aquifers is infiltration or leakage from underlying bedrock aquifers. Human activity may also provide a source of recharge to the aquifers, chiefly by return infiltration of irrigation and percolation of sewage or wastewater. The primary method of estimating recharge in the alluvial aquifers is to calculate discharge from the aquifer, most of which occurs as evapo-transpiration at playas, and to assume inflows are equal to outflows. NDC63 and USG85e provide details of calculation methods and estimates of recharge for the Amargosa Basin; values are discussed in Sections 7.1.2.3 and 7.1.2.4.

The nature and relative importance of potential recharge sources to the Amargosa Desert alluvial aquifer is a matter of some debate. Perhaps the major source of recharge to the alluvial aquifer is lateral flow into the alluvial deposits from the thinning volcanic aquifer to the north (USG86). This is contradicted by USG85f, which uses ground-water geochemical data to argue that “ground water in the west-central Amargosa Desert ....was recharged primarily by overland flow of snowmelt in or near the present-day stream channels, rather than by subsurface flow from highland recharge areas to the north,” and that “much of the recharge in the area occurred during Late Wisconsin time” (USG85f, p F1). This conclusion fails to account for the eventual fate of water in the volcanic units to the north and is probably too restrictive.

The upward hydraulic gradients measured in the lower carbonate aquifer support the idea that much of the outflow from the volcanic aquifer moves into the alluvial aquifer. Although this outflow presumably occurs somewhere between Yucca Mountain and Amargosa Valley, the potentiometric surface, at the scale at which it is currently mapped, provides little indication as to how or where this transition occurs. A recent study, using streamflow data and a modified version of the HYMET model for the Amargosa River, suggests that the alluvial aquifer may also be receiving recharge via upward flow from the carbonate aquifer (INY96).

USG91a shows water level altitude maps for 1950's (predevelopment) conditions in the Amargosa Desert. Comparison of this map with more recent (1987) water level altitude maps indicates that aquifer development may have had a significant impact on water levels and flow directions. Pumping of the alluvial aquifer may have induced upward flow from the underlying lower carbonate aquifer into the alluvial system. The extent to which areal recharge occurs via infiltration of present-day precipitation falling directly onto the alluvial valleys is thought to be minimal. This is because of the infrequent rainstorms and the shallow depths to which rainfall soaks into the desert soil during such events. After a rainstorm, much of this water rapidly evaporates back into the atmosphere (USG85f).

Several potential modes for natural discharge from alluvial basins exist, including interbasin flow to other alluvial basins; leakage to the underlying units, either volcanic or carbonate; and evapotranspiration (NDC63). Discharge from the alluvial aquifers also occurs in the form of ground-water withdrawals by pumping. In the Amargosa Valley alluvial basin, ground water is pumped for domestic and irrigation purposes (USG91a). Quantitative estimates of recharge and discharge from the Amargosa alluvial basin are discussed in more detail in Section 7.1.2.4.

Potentiometric and hydrochemical data indicate that the Alkali Flat (also known as the Franklin Lake Playa), located in the southern end of the Amargosa Desert, is a major discharge area for the alluvial aquifer system. Estimated discharge at Alkali Flat is about 10,000 acre-feet per year (DOI63). Discharge at the playa occurs primarily through evapotranspiration, the principal component of which is bare-soil evaporation (USG90b). Some ground water may flow beneath the mountain at the south end of the playa and continue southward (USG96a). Regional water table maps of the alluvial aquifer (see USG91a) also suggest that a portion of the flow in the alluvial aquifer may be moving southwest through the abutting carbonate rocks of the Funeral Mountains, and discharging into Death Valley. The extent to which this occurs is unknown.

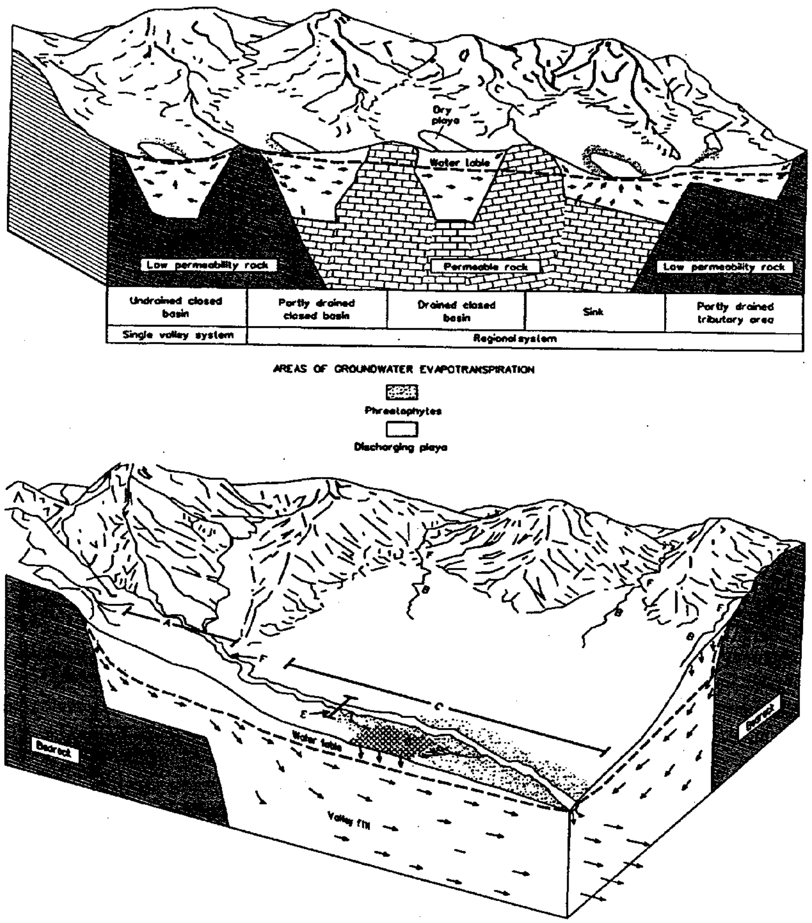
7.1.2.3 Regional Ground-Water Flow and Hydrology

The nature of regional ground-water flow in the Yucca Mountain area is governed by the complex three-dimensional nature of the geological and structural units through which it flows. As previously described, the geological setting in this area involves a basement of Paleozoic 1 sedimentary rocks which have been complexly folded and faulted. The Paleozoic sequence is overlain in many areas by a thick section of volcanic rocks and/or alluvial basin fill deposits. The Paleozoic and volcanic sequences have been disrupted by faults which have juxtaposed various units against one another and created the basin and range structure. The resulting geological and stratigraphic complexity creates a correspondingly complex regional ground- water flow system.

Key to understanding regional ground-water flow in this area is the concept that the large-scale flow system may comprise up to three coexisting ground-water flow subsystems: local, intermediate, and regional. These subsystems exist one on top of the other, as well as side by side. This concept is illustrated in Figure 7-23. The coexistence of such subsystems means that deep regional flow can pass beneath shallow local areas of high permeability and that the presence of hydraulic barriers or variations in permeability can cause appreciable discharge upgradient from the hydraulic terminus of the system. Major flow systems in the Great Basin are defined by the dominant flow system, whether it be local, intermediate or regional. Where consolidated rocks are permeable enough to afford significant identifiable hydraulic continuity on a regional scale, the local and intermediate types of systems are considered to be subsystems with major regional flow systems. Boundaries between systems are only generally defined; some may represent physical barriers to flow, such as masses of intrusive rocks, while others represent ground-water divides or divisions where an area of parallel flow ultimately diverges downgradient.

Regional Ground-Water Flow Systems in the Yucca Mountain Area

The Great Basin is considered to consist of 39 “major flow systems” (USG93b). The study area is located within the Death Valley Ground-Water Flow System (DVGWS) which covers an area of 15,800 square miles (40,100 km^2) in Nevada and California (Figure 7-24). The boundaries of the DVGWS are not precisely known; traditional lateral boundaries are topographic divides that



Gaining reach, net gain from ground–water inflow although in localized areas stream may recharge wet meadows along flood plain. Hydraulic continuity is maintained between stream and groundwater reservoir. Pumping can affect streamflow by inducing stream recharge or by diverting groundwater inflow which would have contributed to streamflow.

Minor tributary streams, may be perennial in the mountains but become losing ephemeral streams on the alluvial fans. Pumping will not affect the flow of theses streams because hydraulic continuity is not maintained between streams and the principal groundwater reservoir. These streams are the only ones present in arid basins.

Losing reach, net loss in flow due to surface water diversions and seepage to groundwater. Local sections may lose or gain depending on hydraulic gradient between stream and groundwater reservoir. Gradient may reverse during certain times of the year. Hydraulic continuity is maintained between stream and groundwater reservoir. Pumping can affect streamflow by inducing recharge or by diverting irrigation return flows.

Irrigated area, some return flow from irrigation water recharges groundwater.

Flood plain, hydrologic regimen of this area dominated by the river. Water table fluctuates in response to charges in river stage and diversions. Area commonly covered by phreatophytes (shown by random dot pattern).

Approximate point of maximum stream flow.

Figure 7-23.Schematic Illustration of Ground-water Flow System in the Great Basin (USG76a)

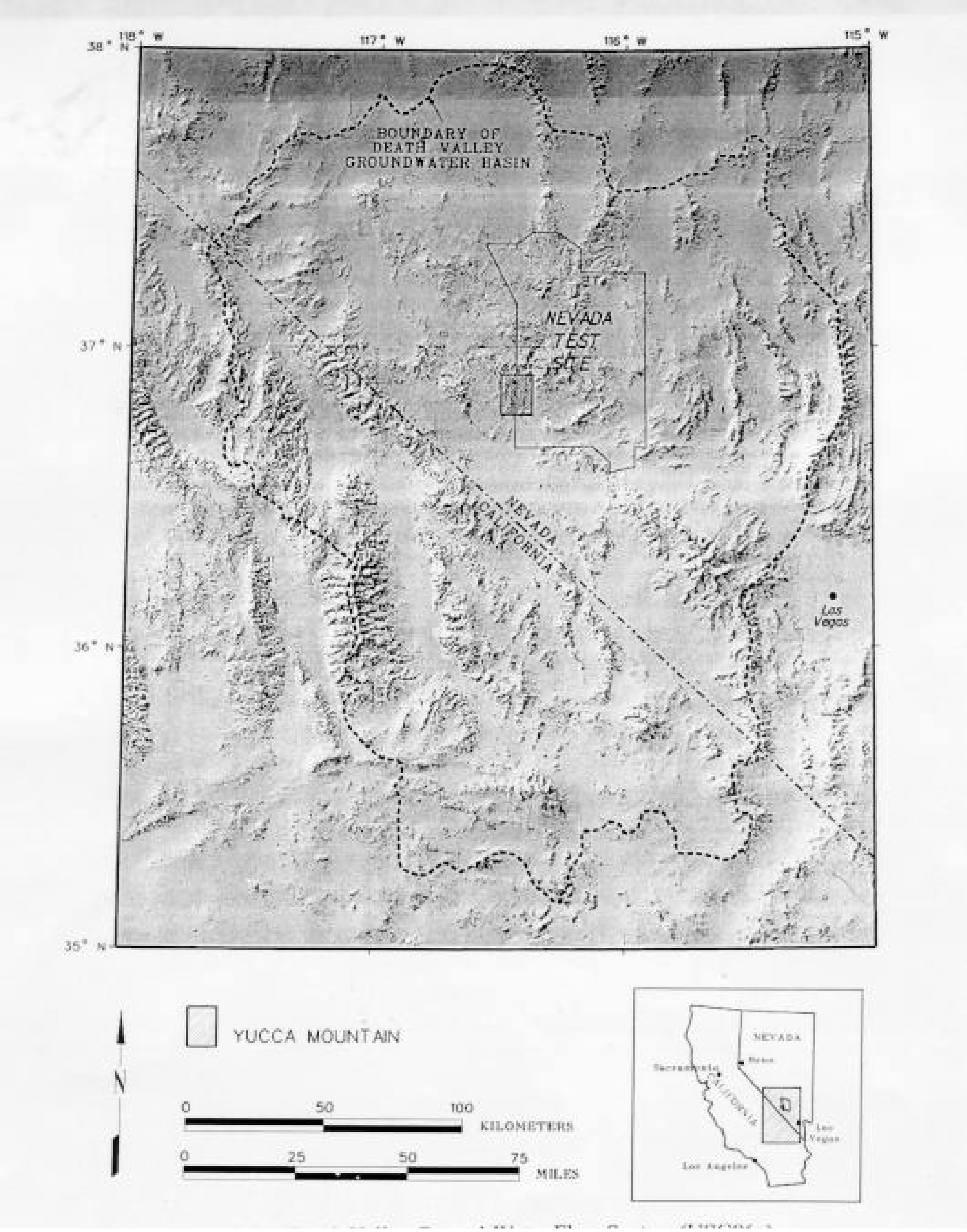


Figure 7-24. Death Valley Ground-Water Flow System (USG96a)

may be physical barriers to ground-water flow or may coincide with ground-water mounds formed by local recharge. Rarely, however, are these boundaries true hydraulic barriers.

The DVGWS is further subdivided into a small number of hydrogeological subareas or basins. Yucca Mountain is located within the Alkali Flats-Furnace Creek Ranch subbasin (Figure 7–25). Definition of the hydrologic boundaries of the basins is greatly hindered by the complexity of the geologic structure, the limited potentiometric data, and most critically, the interbasin movement of ground water through the thick and aerially extensive lower carbonate aquifer (USG75). The basin covers an area of about 2,800 mi^2 and was named after the two major discharge areas near its southern end (USG82c). The principal aquifers in the northern part of the subbasin are volcanic aquifers; valley-fill and carbonate rock aquifers dominate in the southern part. The subbasin receives water from recharge within its boundaries and probably also receives water as underflow from adjoining subbasins. Ground water leaves the subbasin as evapotranspiration at discharge areas or as interbasin outflow (USG96a). Alkali Flat is an area where ground-water discharge occurs almost entirely through evapotranspiration. The other major discharge is thought to be from springs near Furnace Creek Ranch, near the headquarters of the Death Valley National Monument. A 1984 study (USG84g) estimated discharge from the subbasin at about 15,600 acre-ft/yr; of this total, about 10,000 acre-ft/yr discharges at Alkali Flat and the remainder discharges from springs and as evaporation near Furnace Creek Ranch in Death Valley. More recent work (HST91) developed a conceptual model that excluded the Furnace Creek Ranch discharge area from the shallow flow system that includes Yucca Mountain. HST91 reported that a ground-water divide could exist in the Greenwater and Funeral Ranges between the southern Amargosa Desert and Death Valley. Such a divide, if it exists, could limit discharge from the shallow flow system in the Amargosa Desert to the Furnace Creek Ranch area, although it would not necessarily affect the deeper flow system that may also contribute discharge to the Furnace Creek Ranch area.

Adjoining the Alkali Flats-Furnace Creek Ranch subbasin to the east is the Ash Meadows subbasin. These subareas are separated by an irregular north-south line which runs east of Yucca Mountain. In general, ground-water flow in these basins is considered to originate from recharge in the upland areas of the basin and to move in a southerly direction toward discharge points in alluvial basins located in the southern parts of the basins. The southern portion of the boundary between the Alkali Flat-Furnace Creek Ranch subbasin and the Ash Meadows sub-basin is located along a line of springs (Ash Meadows) which coincides with the trace of a buried fault.

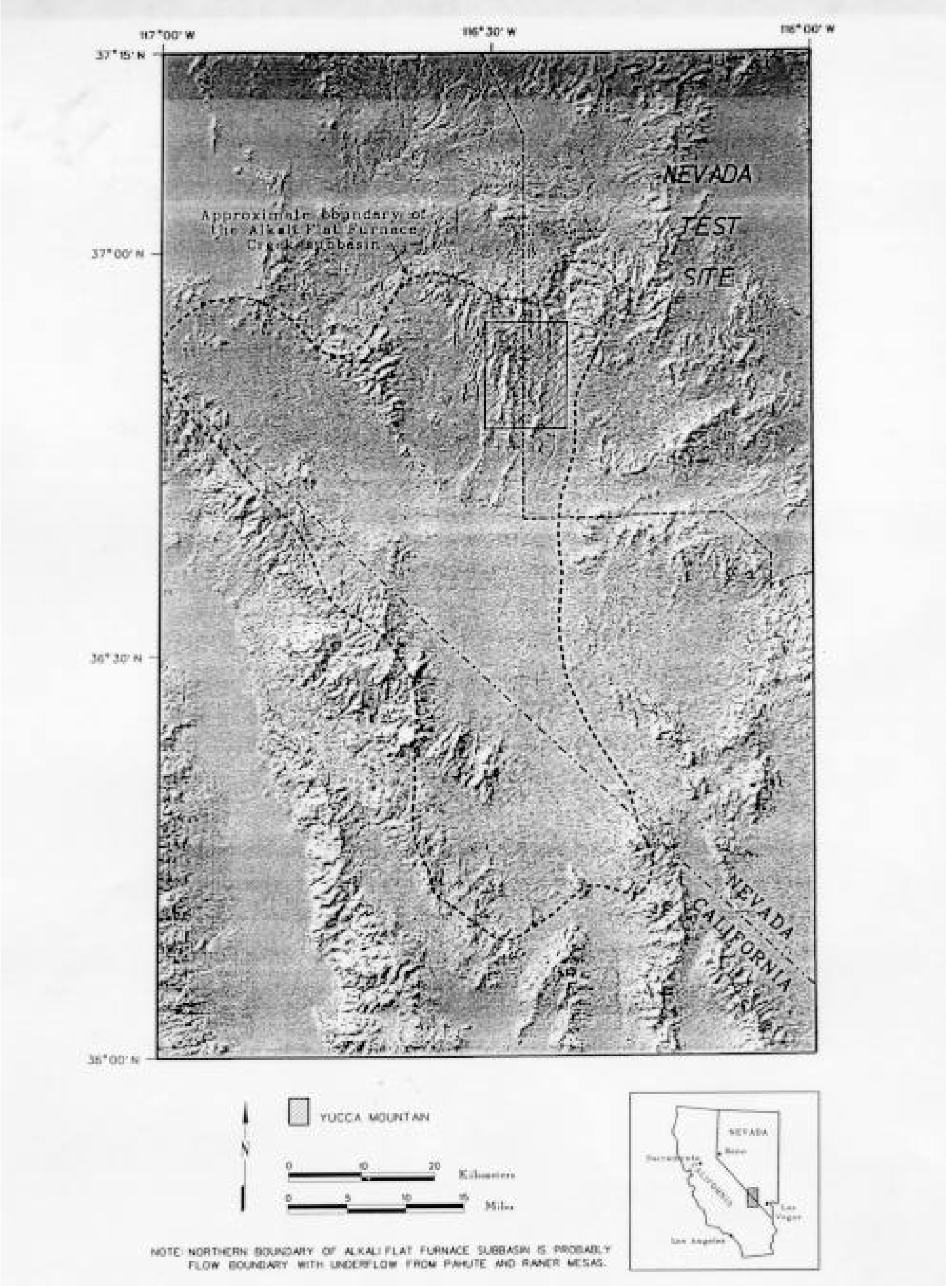


Figure 7-25. Alkali Flat-Furnace Creek Ranch Ground-Water Subbasin (USG96a)

This fault causes water to rise to the surface by juxtaposition of permeable and impermeable units of the Paleozoic rocks. Subsurface outflow into the Alkali Flat-Furnace Creek Ranch subbasin is probable, especially in the vicinity of the buried fault. Geochemical and potentiometric data suggest leakage of water from the carbonate aquifer into the alluvial aquifer east of the fault line (USG85f). The degree of connectedness of the two subbasins may be more significant than localized leakage across the bounding fault. USG96a suggests that "deep hydraulic connection through the carbonate aquifer may connect the Ash Meadows area on the east side of the Amargosa Desert to the Furnace Creek Ranch area of Death Valley. This possible connection is consistent with the observation that the hydrochemistry of water from springs that discharge at Furnace Creek Ranch is similar to the hydrochemistry of water discharging at some springs in the Ash Meadows area. This similarity in hydrochemistry allows the possibility of westward ground-water flow through deep aquifers beneath the Amargosa Desert, whereas flow through the shallower aquifers seems to be predominately southward" (USG96a).

Ground-Water Flow Directions and Potentiometric Surfaces

Within the DVGWFS, recharge from precipitation probably occurs at Timber Mountain, Pahute Mesa, Ranier Mesa, Shoshone Mountain, and the Spring Mountains. In the vicinity of Yucca Mountain, infiltration of runoff in Forty Mile Canyon and Forty Mile Wash probably contributes to recharge. On a regional and subregional scale, ground water is generally considered to flow from these recharge areas to discharge areas located at the southern end of the flow system (USG75). Much of the ground water which travels beneath Yucca Mountain probably discharges at Alkali Flat (Franklin Lake) in the southern Amargosa Desert and/or in the springs on the eastern side of Death Valley. Death Valley is the ultimate ground-water discharge area and is a closed basin; no water leaves it as surface or subsurface flow (USG96a). Numerous workers have constructed potentiometric surface maps for this area, including USG75, USG82c, USG84f, USG91a, and USG94a. Availability and quality of potentiometric data for the subbasin are highly variable. Wells are irregularly distributed throughout the subbasin; the greatest density of wells is on Yucca Mountain itself and in the Amargosa Valley. Data are almost entirely lacking in the mountainous recharge areas north of Yucca Mountain. In the immediate vicinity of Yucca Mountain itself, numerous wells have been drilled to the saturated zone and the potentiometric surface is well-characterized. The potentiometric surface in Amargosa Valley and in the vicinity of Alkali Flat is also relatively well defined by numerous irrigation and monitoring wells. There are almost no potentiometric data available in the Greenwater and Funeral Ranges, which bound the Amargosa Desert on its southwestern side. Figure 7-26 shows the regional potentiometric surface for the DVGWFS. The following sections discuss in detail the nature of the potentiometric surfaces in each of the three main aquifer types.

Volcanic Aquifer

The lateral extent of the volcanic rocks that make up Yucca Mountain is not well defined, primarily because the volcanic units are buried beneath alluvial deposits in the topographically low areas. South of Yucca Mountain, the volcanic section is believed to thin and pinch out somewhere in the vicinity of Lathrop Wells (USG85a, DOE94b). Where the volcanic unit is not present, alluvial deposits presumably directly overlie Paleozoic sedimentary rocks. Where the volcanic units thin south of Yucca Mountain, ground water flowing in the volcanic aquifer discharges horizontally into the adjoining alluvial deposits and continues to flow in a southerly direction beneath the Amargosa Desert.

At the scale of Yucca Mountain, there are significant variations from the regional flow pattern, resulting in local ground-water flow with a strong easterly component. The potentiometric surface beneath Yucca Mountain has been relatively well-characterized. Potentiometric surface maps are presented in USG95a, USG94a, and USG84f, among others. The potentiometric surface can be divided into three regions: 1) a small-gradient area (0.0001) to the southeast of Yucca Mountain, 2) an area of moderate-gradient (of about 0.015) on the western side of Yucca Mountain, where the water level altitude ranges from 775 to 780 m and appears to be impeded by the Solitario Canyon Fault and a splay of that fault, and 3) a large-gradient area (0.15 or more) to the north-northeast of Yucca Mountain, where water level altitudes range from 738 to 1,035 m (USG94a). Numerous theories have been proposed to explain the presence of the three domains and especially the cause of the large gradient area, where water levels decline by more than 900 feet over a distance of slightly greater than one mile. The position of the large gradient area does not correlate well with any observed geologic feature in the upper 1,500 feet of the mountain (FRI91). The area where the gradient has been defined is about 1.7 miles north of the design repository. If the gradient is caused by a barrier to ground-water flow, it could be of particular importance to the design and performance of the repository; an increase in the permeability of such a barrier could cause a substantial rise in water table altitude in the area of the proposed repository. A rise in the water table would decrease the thickness of the unsaturated zone beneath the repository and decrease ground-water travel time from the repository to the accessible environment (SIN89).

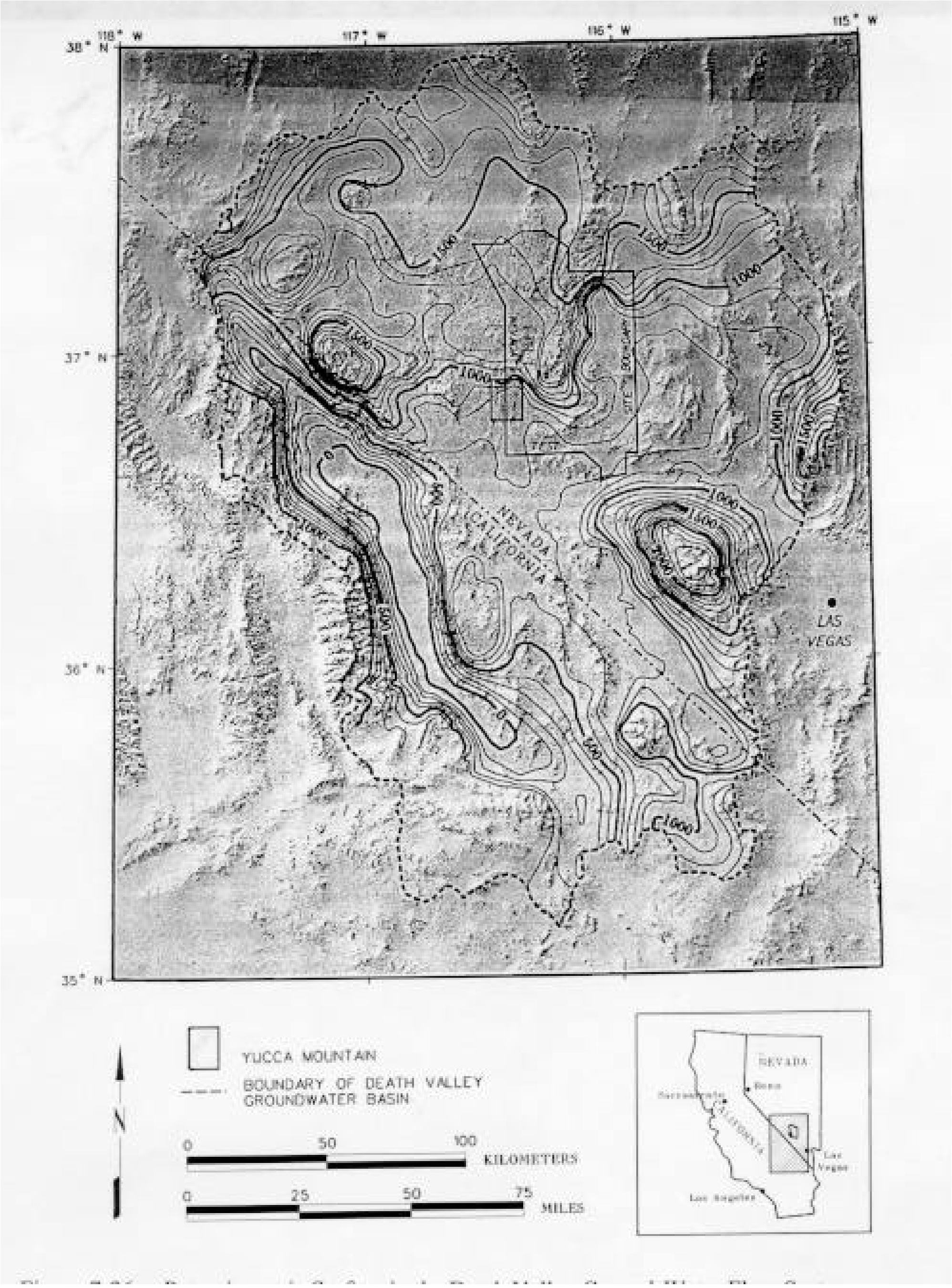


Figure 7-26. Potentiometric Surface in the Death Valley Ground-Water Flow System (USG96a)

Possible causes of the large gradient other than the flow barrier include, but are not limited to: a fault or fault zone; an intrusive dike; a change in lithologic facies or a pinch-out; a change in fracture orientation, density, aperture, or fracture fillings; perched water zones; or some combination of the above phenomena. Fridrich et al. (FRI94) have proposed two models for the large gradient zone, integrating geologic, geophysical and geochemical evidence to support their analysis. These and other authors interpret a northeast trending gravity low and drill hole data to indicate the presence of a buried northeast striking graben (a downdropped block of rock bounded on both sides by faults) immediately south of the water table decline. The large gradient zone is coincident with the northern bounding fault of the proposed graben. The presence of the northern bounding graben fault, which is not exposed at the surface and is not known to have been encountered in any drill holes in Yucca Mountain, is central to both models proposed.

Briefly, the first conceptual model proposes that the buried fault zone provides a permeable pathway through the volcanic section into the underlying deep carbonate aquifer. The second model has the buried fault acting as the northern boundary for a much thicker and more transmissive volcanic section south of the buried fault. These authors also suggest that rapid draining of water in the large gradient zone may cause the low gradient area to the south and southeast. In this model, the small gradient zone may result partly from a reduced ground-water flux in the volcanic rocks due to the capture of flow by the underlying deep carbonate aquifer.

Carbonate Aquifer

The lower carbonate aquifer has a maximum thickness of about 8,000 m. Because the carbonate aquifer in the study area is overlain by thick deposits of volcanic rocks or alluvium, flow directions and gradients are not well-defined. Regional ground-water flow through the lower Paleozoic aquifer is considered to be generally southward. Small-scale potentiometric surface maps are presented in USG75. The lower carbonate aquifer is present below Yucca Mountain at a depth of about 1,000 m and extends southward below the Amargosa Desert into Death Valley. There are a very limited number of holes that penetrate the lower carbonate aquifer beneath the valley fill. Much of the physical knowledge of the system is based upon studies of the outcrop areas, most of which are in the mountain ranges. The best interpretation of available geological data indicates that the lower carbonate aquifer is continuous from beneath Yucca Mountain to

Death Valley and is a potential pathway for radionuclide transport in what appears to be the ultimate discharge point for the aquifer in Death Valley.

The extent of hydraulic communication between the volcanic and underlying Paleozoic sequence is not well characterized. In the only well (UE-25p#1) at Yucca Mountain which penetrated into the Paleozoic sequence, an upward hydraulic gradient (from Paleozoic to the Tertiary) was measured. Analysis of earth-tide response of water levels in this well have been interpreted to indicate that the carbonate aquifer is well-confined by an overlying low-permeability confining layer and has a relatively high transmissivity (INY96). Additional evidence, including isotopic composition and temperatures of ground water beneath Yucca Mountain, supports the concept that ground water may be flowing from the Paleozoic aquifer into the volcanic aquifer (USG88c; STU91).

Alluvial Aquifer

Significant amounts of ground water occur in the alluvial aquifer beneath the Amargosa Desert. In the Amargosa Valley area, irrigation activity derives all of its water from wells completed in the alluvial aquifer, some of which yield water at rates of several hundred gallons per minute. Static water levels are less than 55 m below the surface in some locations. Figure 7-27, taken from USG91a, shows a map of the water table in the Amargosa Desert. USG91a also provides a map of depth to water in the Amargosa Desert. Ground-water flow in the alluvial aquifer is generally perpendicular to the potentiometric contours. The potentiometric contours shown in Figure 7-27 indicate that the predominant flow direction is to the south. The ground-water flow direction is also roughly parallel to the surface drainage direction. At the southern end of the Amargosa Desert, low permeability playa and lake bed deposits create locally-confined conditions. The potentiometric surface at Alkali Flat is in some locations above the ground surface (USG90b).

The potentiometric surface shown in Figure 7-27 is drawn from 1987 data. Comparison of this map with water level altitude maps for 1950’s (predevelopment) conditions (USG91a) in the Amargosa Desert indicates that irrigation pumping has had a significant impact on water levels and local flow directions. Pumping of the alluvial aquifer may also have induced upward flow from the underlying lower carbonate aquifer into the alluvial system.

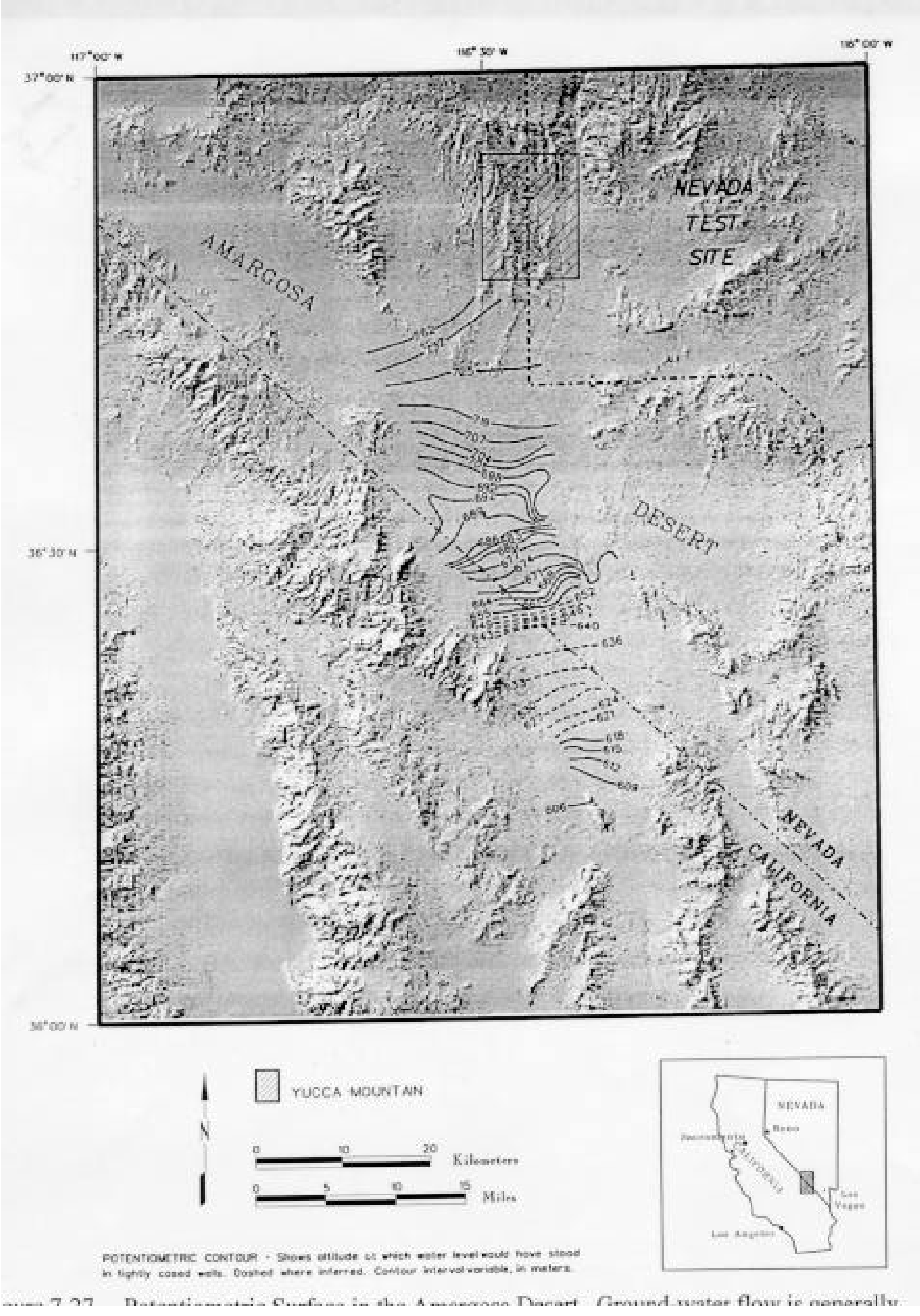


Figure 7-27. Potentiometric Surface in the Amargosa Desert. Ground-water flow is generally south, perpendicular to contour lines. (USG90b)

Ground-Water Travel Times and Radionuclide Transport

The transport of radionuclides in the saturated zone away from a repository depends on a wide variety of factors including, but not limited to, ground-water and host rock geochemistry; advective ground-water velocities; radionuclide concentrations and retardation properties; flux rates of radionuclides from the unsaturated zone; the presence of sorbing materials such as zeolites and clays; rock fracture density; fracture-matrix interaction; future climate changes; and anthropogenic influences. Knowledge of the transport properties in the site-scale and regional flow systems would allow researchers to more completely address four of the most important questions surrounding repository performance and regional ground-water flow issues in the area around Yucca Mountain:

1. What path would radionuclides from the repository follow?
2. How fast and how far would radionuclides travel in the saturated zone?
3. Where would radionuclides become accessible to the biosphere?
4. What will the concentrations of radionuclides be when they become accessible to the biosphere?

The answer to all of these questions is uncertain. The ability to know or predict the answers to these questions depends on performing sufficient scientific investigations over the study area in order to reduce the associated uncertainties to acceptable levels. Some level of uncertainty will always remain, as it is not possible to completely characterize any underground system.

Recent testing activities conducted at the C-well complex have been designed to provide more information regarding contaminant transport properties in the saturated zone (DOE96a, DOE96b). Tracer testing at the C-wells complex has included the injection of both conservative (non-sorbed/non-decaying) and nonconservative tracers (sorbed). All tracer tests were performed by establishing a quasi-steady convergent flow field and hydraulic gradient by pumping from borehole UE-25 c#3 for several days prior to the injection of tracer compounds. Test results are collected by analyzing samples taken at regular intervals from the pumped well and preparing “breakthrough curves” which plot the concentration of the tracer in the pumped well versus time. After the first detection of tracer compound, breakthrough curves typically show an initial rapid rise in tracer concentration, which then peaks and tails off gradually.

The first tracer test performed at the C-wells used sodium iodide, a conservative solute. Because it is negatively charged, sodium iodide does not sorb to zeolites and clays, and has an average matrix retardation coefficient of 0.93. The retardation coefficient should be less than one because of a process known as anion expulsion, wherein anions are repelled by negatively charged grain surfaces and arrive at the recovery well prior to neutrally-charged tracers. Test conditions were negatively impacted by decreasing pump discharge and the resulting nonsteady hydraulic gradient and flow rates. Tracer recovery data were analyzed to determine effective porosity and longitudinal dispersivity using an analytical solution. The analytical method employed has a high uncertainty and calculated parameters do not represent a unique solution to the breakthrough curve data. Test data were analyzed using several different sets of assumptions including a single-porosity solution, a weakly dual-porosity solution, and a moderately dual porosity solution.

In a single-porosity solution, calculated fracture porosity was 0.036 and longitudinal dispersivity was 17.00 ft. In a weakly dual-porosity solution, calculated matrix porosity was 0.032, fracture porosity was 0.0068, and longitudinal dispersivity was 20.75 feet. In a moderately dual-porosity solution, good matches were obtained using a matrix porosity of 0.0778, a fracture porosity of 0.0237 and a longitudinal dispersivity of 13.64 feet. It is important to recognize that parameters used in analyzing tracer recovery data have a high degree of uncertainty and that because the ground-water flow field at the C-wells is anisotropic, the transport field is most likely anisotropic as well.

Subsequent to performing the conservative tracer test, two additional pilot tracer tests were performed. Both tests were conducted in the 100 meter thick isolated interval within the Bullfrog member of Crater Flat Tuff. This interval has the largest hydraulic conductivity of any interval at the C-holes. The objectives of these tests were to determine: 1) which injection well (c#1 or c#2) would result in a higher peak concentration of a conservative tracer, and thus be a better injection well for a reactive tracer test, and 2) what minimum mass of lithium bromide would have to be injected to conduct a successful reactive tracer test. Both pilot tests were successful in that they clearly identified that Well c#2 is the preferred injection hole for a reactive tracer test and that at least 80 kilograms (kg) of lithium bromide would be needed to ensure a successful test. The analysis of these tracer tests and any subsequent tests for transport parameters is not currently available.

The current state of knowledge suggests that ground water beneath the proposed repository moves laterally downgradient until the volcanic aquifer pinches out, at which point it discharges laterally into the alluvial aquifer. Radionuclides dissolved in ground water would potentially follow a similar path. Much of the ground water that enters the alluvial aquifer currently moves southward to the primary discharge location at Alkali Flat. Other actual or potential points of discharge for the system include water wells in the Amargosa Desert and springs in the Furnace Creek Ranch area of Death Valley.

Ground-water travel times to any of these locations are not well known. Estimates of ground-water travel times can be developed by simple calculations or by more sophisticated numerical modeling. In either case, travel times calculations are based on hydraulic gradient, hydraulic conductivity, and effective porosity of the formation through which the water is flowing. Of these three parameters, hydraulic gradients are probably the best known and most easily measured. A range of ground-water travel times in the Tertiary volcanic aquifer has been developed in support of DOE’s Total System Performance Assessment conducted in 1993. TSPA93 predicted a range in advective velocities between 5.5 and 12.5 m/yr. These velocities represent average velocities in the Tertiary volcanic aquifer between the footprint of the potential repository and a 5 km “accessible environment” located to the south and east of the potential repository (DOE95f). Performance assessment parameters and results are more fully described in Sections 7.3 and 7.4.

A more recent study on radionuclide transport in the saturated zone (DOE96c) concluded that an advective travel time of five m/yr is in the middle of the range of reasonable estimates. At this velocity, unretarded radionuclides would take approximately 1,000 years to travel five km from the repository and 5,000 years to travel 25 km from the repository. This study also documents the results of preliminary, highly simplified radionuclide transport modeling work performed using advective velocities of five m/yr. The nature of downgradient breakthrough curves and resulting peak dose calculations were highly dependent on assumed values of dispersivity. The study also found that the breakthrough curves, travel times, and peak dose results were strongly dependent on the retardation properties of individual radionuclides, the presence of sorbing materials such as zeolites, and the possibility of fracture transport bypassing sorptive horizons within the volcanic aquifer.

No reliable estimates of advective velocity in the alluvial aquifers have been made downgradient of the potential repository.

An important unresolved issue is the extent of interaction between the volcanic aquifer and the underlying carbonate aquifer. The possibility that radionuclides might enter the regional lower carbonate aquifer, with its higher permeability, raises concerns that radionuclides could be transported as far as Death Valley. Current evidence, such as hydraulic head measurements in UE-25 p#1, isotopic data, and saturated zone temperature anomalies suggests that the lower carbonate aquifer has a higher hydraulic head than the overlying units. This upward gradient indicates that it is unlikely that radionuclide contaminants will be transported into the carbonate aquifer in the vicinity of Yucca Mountain. Velocities through the lower carbonate aquifer range from an estimated 0.02 to 200 feet per day, depending upon geographic position within the flow system (USG75). It should be noted that the figures given above are for an area of carbonate rocks outside, and much larger, than the study area. No data are available regarding actual ground-water flow velocities in the study area. Carbonate rocks with solution-widened fractures, cavities, and caves typically exhibit an extremely large variation in ground-water velocities. Ground-water age dating (WIN76) using carbon-14 methods in the springs of Ash Meadows suggested ages of ground water in the majority of the springs ranging from 19,000 to 28,000 years. INY96 describe more recent studies which indicate that water may move through the lower carbonate aquifer in times less than 1000 to 2000 years.

7.1.2.4 Ground-Water Resources and Utilization

Many of the studies performed in the Yucca Mountain characterization process have thus far focused narrowly on the immediate area in and around the proposed repository. Few studies to date have attempted to present a regional picture of ground-water resources for the areas downgradient from Yucca Mountain. This section presents a summary description of water resources in the area downgradient (generally south) of Yucca Mountain.

Water Quality

Volcanic Aquifer

The chemistry of water flowing through the volcanic aquifers exhibits complex dependency upon rock composition, residence time in the aquifer, and position along a flow line (USG75). Ground-water chemistry in a volcanic rock is controlled by primary glass, pumice fragments, and the diagenetic minerals (NAN89). Water samples from wells drilled in Yucca Mountain indicate that the water is predominantly a sodium bicarbonate water containing small concentrations of silica, calcium, magnesium, and sulfate (USG83). Sodium levels are generally elevated in these rock types due to the presence of volcanic glass, which is not stable in the presence of water and contains appreciable sodium. Two water wells, J-12 and J-13, currently supply water for site characterization activities at Yucca Mountain and have been pumped extensively for decades with no signs of deteriorating water quality (USG83; USG94b). (Additional sources of information regarding ground-water chemistry can be found in USG86, USG84d, USG91b, USG91c, and USG93a.)

With the exception of substances deliberately introduced into wells during drilling and testing, such as drilling fluids (including diesel fuel at Well J-13 (USG83)) and radioactive tracers (Iodine-131; USG93a), no anthropogenic effects on water quality are observed in the volcanic rocks. This is attributed to the relatively low levels of human activity and the presence of a thick unsaturated zone with long travel times for infiltration to reach the saturated volcanic rocks.

Alluvial Aquifer

The chemical quality of the ground water in the saturated alluvial deposits varies from place to place. In general, ground water in wells closer to Yucca Mountain is of better quality than near the ultimate discharge areas of the system, such as the southern Amargosa Desert and Death Valley. Ground water near these latter areas contains higher concentrations of dissolved constituents and is less suitable for most purposes (NDC63). NDC63 states that "although the chemical quality of ground water in the Amargosa Desert may be suitable generally for irrigation, water of median salinity is common and water of high salinity occurs locally." Ground water in the alluvial aquifers in many cases contains excessive concentrations of fluoride; a dental examination of school children in Beatty found that 19 out of 20 children who lived in Beatty since birth were affected with dental fluorosis (NDC63). (See USG94b and USG91d for additional ground-water chemical quality data for the alluvial aquifer.)

Carbonate Aquifer

In general, water occurring in the carbonate rocks is a calcium and magnesium carbonate water. Where water in the carbonate aquifer has moved through the overlying volcanic rocks, analyses show increased levels of sodium and potassium (USG75). See USG84c for chemical analyses of water from Well UE-25 p#1 completed in the carbonate aquifer beneath Yucca Mountain.

7.1.3 Climate Considerations

For the purposes of this document, climate is defined as the ensemble of weather conditions over time. Precipitation and temperature variability are the aspects of climate that are most significant to the long-term performance of a high-level waste repository at Yucca Mountain. These parameters influence, directly and indirectly, water infiltration rates in the area of the proposed repository.

“Variability” means the timing, rates of change, magnitude, and persistence of conditions. Inferences about variability are based on studies of past conditions in the region, as recorded by both geological and biological paleo-environmental indicators. Computer models of the atmospheric circulation are used to simulate both past and future climatic regimes. Modelling results are compared to paleo-data. The better their simulations of past climatic conditions, the more confidence scientists and policy makers will have in the ability of models to predict future climate. Thus, paleo-data are considered essential in assessing future climates.

The impact of human interference with naturally-occurring climate variations must also be considered. Large-scale changes in atmospheric composition have occurred and are almost certain to continue for the next several thousand years (HOU92). General circulation models may be used to anticipate the consequences of such changes and to help chart the future course of climate change. Since the concentration of greenhouse gases in the 21st century will likely exceed anything the world has experienced for millions of years, the paleo-record may not fully define the climate of the future. Unknown feedbacks or abrupt, rare changes in the climate system may occur in the future. Nevertheless, the paleo-record, combined with realistic computer models of existing and future climate, provide the best set of tools currently available to define the potential limits of climate variability in the Yucca Mountain area.

7.1.3.1 Past Climate Conditions and Variations

Global climate has evolved over glacial to interglacial time scales in response to changes in orbital forcing (the relative position of the earth to the sun, with consequent changes in the geographical and seasonal distribution of incoming solar radiation). In simple terms, these changes altered the Pole-Equator temperature gradients, which led to changes in atmospheric circulation and the overall hydrological balance of the earth. These changes caused ice sheets to accumulate on the continents at high latitudes, the sea level to fall, global temperatures to decrease, and rainfall patterns in the tropics to shift.

Changes in incoming solar radiation alone were insufficient to bring these environmental changes about; they were amplified by internal feedbacks of the climate system itself, most probably through changes in atmospheric composition and the albedo (reflectivity) of the earth's surface. Such feedbacks led to reduced levels of carbon dioxide and methane (both greenhouse gases); a higher overall albedo for the earth, due to more extensive snow and ice cover; and more extensive deserts. However, at other times in the cycle of orbital changes, feedback mechanisms brought about increases in greenhouse gases and other changes in the climate system, eventually leading to rapid destruction of the ice sheets and abrupt deglaciations. The growth and decay of ice sheets affected the atmospheric circulation, displacing jet streams equatorward and causing massive increases in rainfall in previously dry areas.

Southern Nevada and the Great Basin experienced such dramatic changes, which, together with lower temperatures, led to aquifer recharge and the filling of many closed basins with extensive lakes. Such changes are evident in geologic features of the region. Variations in lake levels extending back into the last glaciation are best known; they are generally well-dated and have been studied in many areas of the western United States. Observed changes are well supported by a variety of biological evidence, particularly that obtained from the analysis of packrat middens, which contain discrete samples of local vegetation in the vicinity of the packrat nests from particular time periods in the past. For example, when lake levels were high, vegetation was generally more extensive; some areas that are arid today were forested. This can be seen from the packrat middens, where vegetation can be related to past time periods.

Hydrological changes in the arid western United States do not coincide in detail with the record of continental ice volume changes. However, it is clear that high lake levels were present when the Laurentide Ice Sheet was extensive and that water levels fell in association with deglaciation. As noted by Smith and Street-Perrott, "more than a hundred closed basins in the western United States contained lakes during the Late Wisconsin [the last episode of the ice ages], 25,000 to 10,000 yr B.P. [before present], but only about 10 percent of the lakes are perennial and of substantial size today...." Even in today's hyperarid Death Valley, there is evidence that an extensive lake occupied the basin between 21,500 and 11,900 years ago (SMI83; HOO72).

The longer term record of hydrological variability is much harder to document, given the problems of dating water levels and precipitation. In addition, it is possible that some paleo-lakes may have been caused by slight tectonic changes or other geomorphological factors. Furthermore, rapid changes in ice sheet size, as postulated from sedimentary records in the North Atlantic and elsewhere, may have resulted in very abrupt changes in the hydrological regime in the western United States.

If jet stream displacement, due to ice sheet growth and decay, is the principal factor in hydrological change in the western United States, there is good reason to suspect that a quite variable hydrological regime has influenced the region over glacial-interglacial timescales. Nevertheless, the more prolonged glacial episodes were dominated by cooler, wetter conditions, associated with higher infiltration rates, more vegetation, and the presence of many freshwater lakes in the Great Basin. Quantifying such changes is difficult, but Spaulding et al. estimate the limit at the last glacial maximum as approximately 6°C colder, with precipitation levels double those of today (SPA83).

7.1.3.2 Potential Future Climate Conditions

Orbital variations clearly have driven the broad-scale variations of global climate over the last several million years, at least. These orbital variations are likely to be a dominant influence in the future. Since the orbital variations are periodic and predictable, their occurrence in the past and in the future can be calculated. Variations over the past million years have occurred within a fairly limited envelope; predicted variations for the future show that, for at least the next 250,000 years, the expected orbital changes will stay well within this envelope. How such changes will affect climate can be assessed by using the solar radiation changes to force a global climate model to simulate both past and potential climate variations in the future.

Most studies attempt to reconstruct past changes where the simulations can be verified by observation, but a few attempts have been made over the past 25 years to forecast future changes, at varying levels of sophistication. Figure 7-28 shows the results of these efforts, with the overall parameter describing the output expressed (on the righthand side) in terms of global temperature. Obviously, the sophistication of such calculations has increased over the years, but most studies consistently predict that global climates over the next 60,000 years or so will gradually shift towards a full glacial mode, similar to that experienced 20,000 years ago during

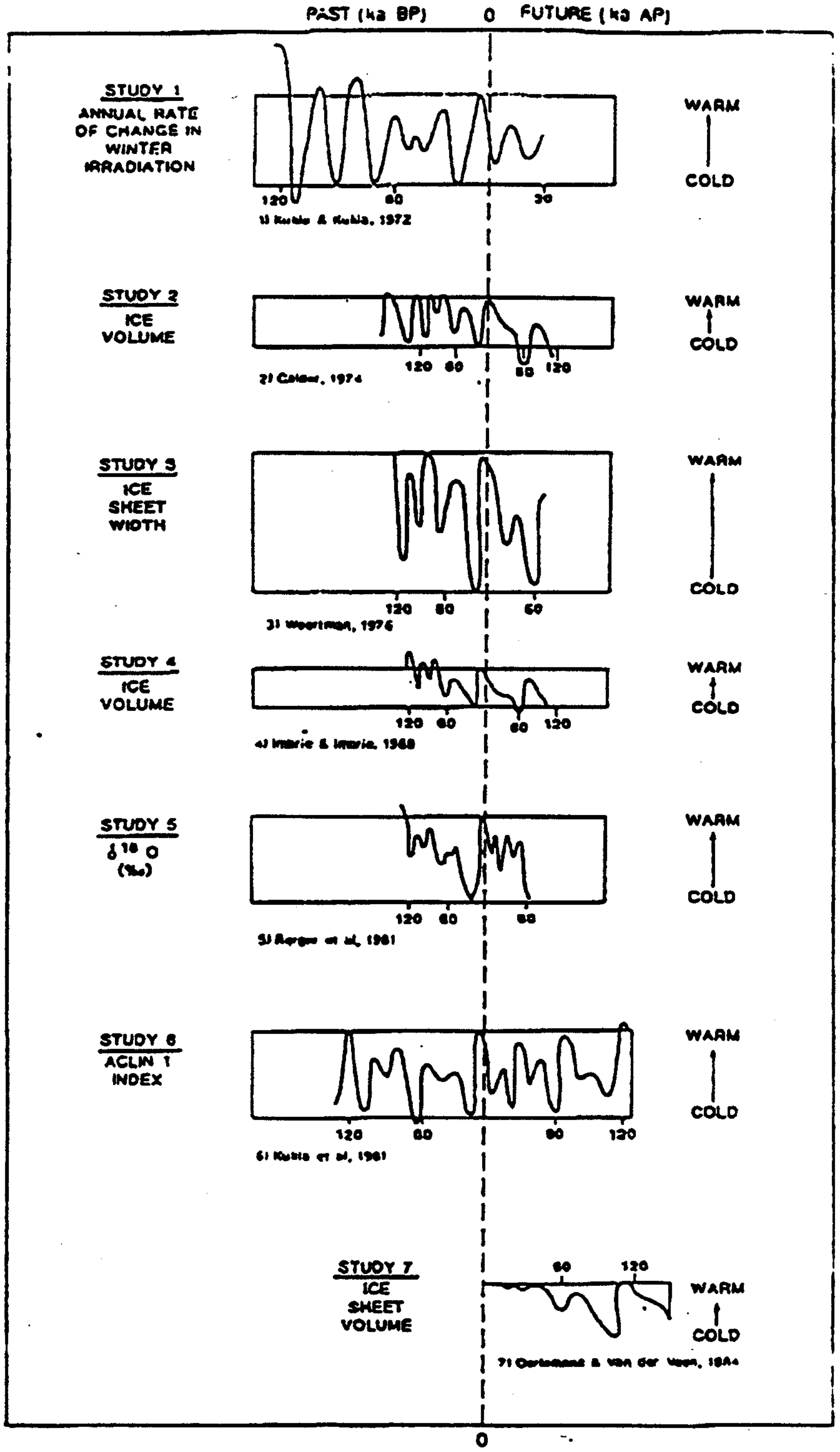


Figure 7-28. Future Climates, Expressed in Terms of Overall Global Temperature Change

Future climates, expressed in terms of overall global temperature change, as predicted by seven different models driven by changes in orbital forcing. The boxes on each diagram delimit the last glacial and interglacial extremes. Dates are in years x 10^3. (GOO92) the most recent glacial period. Indeed, the trend towards such a state began a few thousand years ago, in the mid-Holocene Period.

The trend towards a glacial extreme is not monotonic, but involves minor oscillations on a generally downward trend in temperature. Following the temperature minimum, there is some indication that conditions like those of today will not return again until about 120,000 years into the future. It also appears that the "saw-tooth" nature of past climate variations--slow declines to cold glacial conditions, followed by abrupt "terminations" of glacial conditions--will also continue into the future.

In general, the present arid climate conditions are expected to be maintained in the future. The Sierra Nevada Mountains, which lie to the west of Yucca Mountain, have a strong rain-shadow effect on the Yucca Mountain Region. This effect is expected to be maintained or enhanced in the future because the Sierra Nevada range is still increasing in elevation (DeW93).

These are very broad conclusions that do not allow for the high-frequency oscillations, superimposed on longer term trends, which have been seen in the Greenland ice cores and in some marine sedimentary records from the North Atlantic. High-frequency oscillations have most recently been seen in the Santa Barbara Basin (BEH96). Such changes would be expected to occur in any future glaciation, since they appear to be integrally linked to the dynamics of ice growth and decay and their impact on ocean circulation (BRO94).

What these models do not consider is the potential additional effects of greenhouse gas increases on the radiative balance of the earth and, consequently, on the general atmospheric circulation. It is generally believed that the small insolation changes brought about by orbital changes are insufficient by themselves to bring about glaciation, or indeed to terminate glaciations. The critical issue is the feedbacks, which may amplify the small radiative signal, with the ice sheets themselves playing a major role (via albedo effects, sea-level change, topographic influences on atmospheric circulation, effects on ocean thermohaline circulation, etc.). What is not clear is whether any near-term increase in greenhouse gases (in the next few decades to centuries) would eventually be overwhelmed by the orbitally-induced shift toward future glaciation or if the warmer climate would preclude such a development by minimizing the necessary feedback mechanisms. Broecker (BRO75) termed this near-term warm episode a "super-interglacial" because it may involve temperatures higher than in any recent interglacial period. As such, it is difficult to predict what the overall consequences of such a unique state might be for the future evolution of climate.

One study of such a scenario used a 2.5D general computer model to assess both anthropogenic effects *and* orbital forcing (BER91). The model assumes that the Greenland Ice Sheet will be entirely consumed in the near term, but that *the general direction of long-term climate change towards glaciation is not changed.* The peak timing of the next glaciation is delayed by about 5,000 years (Figure 7-29). However, this model is still fairly crude and does not incorporate many of the feedbacks that may be critical in the evolution of future climate. More experiments with transient climate simulations, using the next generation of coupled ocean-atmosphere general circulation models, will be needed to obtain a more sophisticated answer to this question.

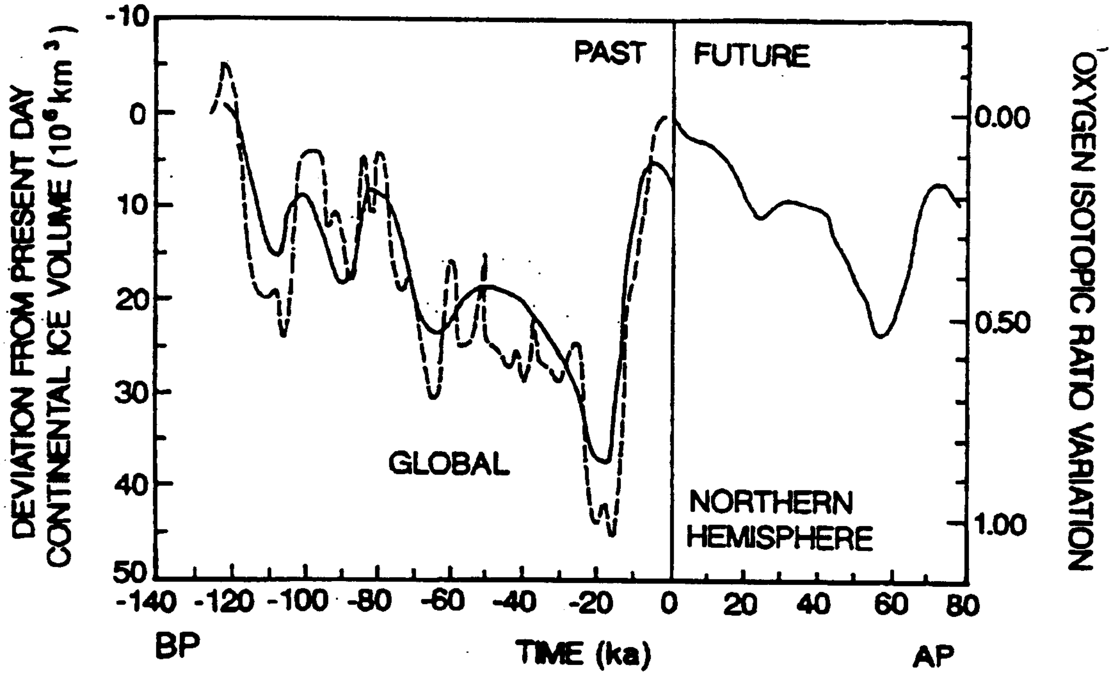


Figure 7-29. Model Simulations of Past and Future Climate Conditions
Model simulations (solid line) of past and future climate conditions, expressed in terms of changing ice volume on the continents, and including anthropogenic greenhouse effects in the immediate future. Dashed line gives past global ice volume changes as registered by oxygen isotope ratios in benthic foraminifera from the oceans (BER91).

At this stage, there is no compelling evidence that the world of the next million years will not be subjected to the same range of climate variations experienced over the last million years. However, in the near term (from the next few decades to several thousand years), an enhanced greenhouse effect will very probably bring about warmer conditions than have been experienced for thousands, perhaps even hundreds of thousands of years. This was the general conclusion of experts who were asked to assess the magnitude and direction of future climate change (Figure 3-11 in DeW93). They estimate that the likely upper limit of a temperature increase in the mean annual temperature of the Yucca Mountain Region would be about two to three degrees celsius. Whether this effect will persist for hundreds or thousands of years depends greatly on assumptions made about future energy consumption patterns and the overall availability of fossil fuels. If society eventually limits fossil fuel consumption, this warmer episode may come to a close, with the naturally-occurring trends then becoming dominant. Nevertheless, the possibility that a greenhouse gas-induced “super-interglacial” may lead to unanticipated pathways in the climate system and new climate states can not be entirely ruled out (BRO87).

The potential changes of greatest concern at Yucca Mountain are those associated with the “glacial climate mode” rather than with an “interglacial mode.” Past history indicates that wetter conditions in the region have generally been associated with globally cooler climates, or with transitions to such climates. Interglacial periods have been arid. Currently, no evidence suggests that this basic pattern is likely to be different in the future. Hence, the immediate future climate of Yucca Mountain, dominated by anthropogenic effects, is likely to be as dry or drier than the present. Eventually, however, cooler and wetter conditions will dominate the area during persistent glacial climate modes.

7.1.3.3 Summary Regarding Climate

The climate in the Yucca Mountain region is currently warm and semi-arid, with a mean annual average temperature of 16°C (61°F) and mean annual precipitation of 170 mm/yr (6.7 in/yr). Precipitation varies throughout the year, averaging about 18 mm/month in the fall and winter, and about 9 mm/month in the spring and summer.

Physical evidence of past climates shows that climate conditions previously cycled between cold glacial climates and warm interglacial climates such as the present. Fluctuations averaged about 100,000 years in length. Present climate conditions have prevailed since the last glacial period about 10,000 years ago.

Infiltration, into Yucca Mountain, of water from precipitation is a factor of primary importance to performance of a potential repository at the site. Projections of future climate conditions, precipitation rates, and infiltration rates are therefore key factors in total system performance assessments such as are discussed in Section 7.3.

The historical record of climate conditions and climate changes in the Yucca Mountain region was interpreted quantitatively by DOE for modeling of future climate conditions in the Total System Performance Assessment for the Viability Assessment (TSPA-VA; see Section 7.3.2). For these performance evaluations, DOE assumed that there would be three characteristic climate conditions in the future: the present-day dry climate, a long-term-average (LTA) climate, with precipitation at levels twice the present, and a superpluvial climate, with precipitation three times the current rates. The climate conditions were assumed to alternate in sequence, with average durations of 10,000, 90,000, and 10,000 years for the present-day, long-term-average, and superpluvial conditions, respectively. For the base-case TSPA-VA evaluation of future repository performance, the present day climate was assumed to continue for 5,000 years into the future, and the first superpluvial climate period was assumed to occur about 300,000 years in the future.

For the TSPA-VA performance evaluations, the average annual precipitation rates were assumed to be 170, 340, and 510 mm/yr, for the present-day, LTA and superpluvial climates respectively. These precipitation rates were assumed to result in average infiltration rates of 7.7, 42, and 110 mm/yr. The three-fold increase in precipitation rate for the superpluvial climate, in comparison with the present-day climate, was therefore assumed to result in a factor of 14 increase in water infiltration into the mountain.

7.2 REPOSITORY CONCEPTS UNDER CONSIDERATION FOR YUCCA MOUNTAIN

7.2.1 Conceptual Repository Systems

Design concepts for a repository at Yucca Mountain have changed and evolved significantly during the 20 years of site evaluation work to date. Changes have been made in response to information from sources such as site characterization data, repository system performance assessments, external technical reviews, and evolution of a waste isolation strategy. Changes have occurred in fundamental concepts as well as in design details. For example, the Site Characterization Plan issued in 1988 (DOE88) envisioned vertical emplacement of waste packages in individual boreholes in the floor of tunnels; current plans call for end-to-end horizontal emplacement in long, excavated drifts. The 1988 waste package design concept was a simple steel canister approximately two feet in diameter with an expected lifetime of 1,000 years or less; the current design concept is a container about six feet in diameter with two-layer, corrosion-resistant walls and a lifetime objective of more than 10,000 years. Other changes have evolved as a result of acquisition of site and laboratory data and from consideration of the results of total-system performance assessments.

In response to requirements of the Fiscal Year 1997 Energy and Water Appropriations Act (PL 104-782), the DOE performed a Viability Assessment (VA)[21] for development of a repository for disposal of highly radioactive wastes at Yucca Mountain. The purpose of the VA was to provide policy makers with an estimate of the viability of a repository at the Yucca Mountain site in the time frame required for decision making.

The five-volume VA report was released by the DOE in December 1998 (DOE98). The Department found "... that Yucca Mountain remains a promising site for a geologic repository and that work should proceed to support a decision in 2001 on whether to recommend the site to the President for development as a repository" (DOE98, Overview).

The design concepts used for the VA are described below. DOE considers the VA, and its repository design features, to constitute a snapshot in time of an evolutionary process leading potentially to a finding that the site is suitable for disposal and subsequently to a License Application. Further development of the repository design features and performance evaluation methodology will be needed for the Site Recommendation and for a License Application if the site is found to be suitable for disposal.

Design concepts used by the DOE in the Viability Assessment were as follows:

- Horizontal emplacement of waste packages in parallel excavated drifts.
- An initial thermal loading on the surroundings corresponding to 85 MTU/acre.
- Emplacement of waste packages only between the Ghost Dance fault and the Solitario Canyon fault.

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[21] The terms Total System Performance Assessment-Viability Assessment and Viability Assessment and the acronyms TSPA-VA and VA are used interchangeably throughout this report.

- Disposal of 63,000 MTU of commercial spent fuel and 7,000 MTU equivalent of various types of defense wastes. A total of 10,500 waste packages would be emplaced, consisting of 7,642 packages of commercial spent fuel and 2,858 packages of defense wastes.

- Disposal in excavated drifts 5.5 m in diameter, with a total of about 107 km of tunnels and drifts in an emplacement area of 740 acres. Drifts would be spaced 28 m apart.

- Packages of commercial spent fuel would contain 21 PWR fuel rod assemblies or 44 BWR assemblies.

- Waste package design features which include, for the commercial spent fuel packages, dimensions of 2-m diameter and 6 m length, with an outer shell of A 516 carbon steel 10 cm thick and an inner shell of corrosion-resistant Alloy 22 that is 2 cm thick.

- Temperature limits of 200°C for the drift walls and 350 ^{0}C for the commercial spent fuel cladding.

Waste types to be disposed would include uncanistered and canistered commercial spent fuel assemblies; canisters of vitrified defense high-level wastes; navy spent fuel; other DOE-owned spent fuel, such as from the Hanford N-reactor; and surplus plutonium from dismantled nuclear weapons. Most of the commercial SNF is clad with zirconium alloys (Zircaloy-2 and Zircaloy-4); about 1.15% is clad with stainless steel. In the VA, the DOE assumed that the Zircaloy cladding would act as a significant barrier to radionuclide release. No credit was taken for stainless steel cladding.

7.2.2 Design Concepts for Engineered Features of the VA Repository

7.2.2.1 Repository and Surface Facility Layouts

The VA reference design for excavation of tunnels and drifts for emplacement of wastes is shown in Figure 7-30. The repository footprint, which covers about 740 acres, is offset from both the Ghost Dance and Solitario Canyon faults. The footprint is about 1 km wide and 3 km long. This layout resulted from consideration of factors such as potential for fault movement, location of dominant fracture systems in the geologic formations, ease of access during operations, and the heat emissions and temperature limits assumed as the basis for establishing

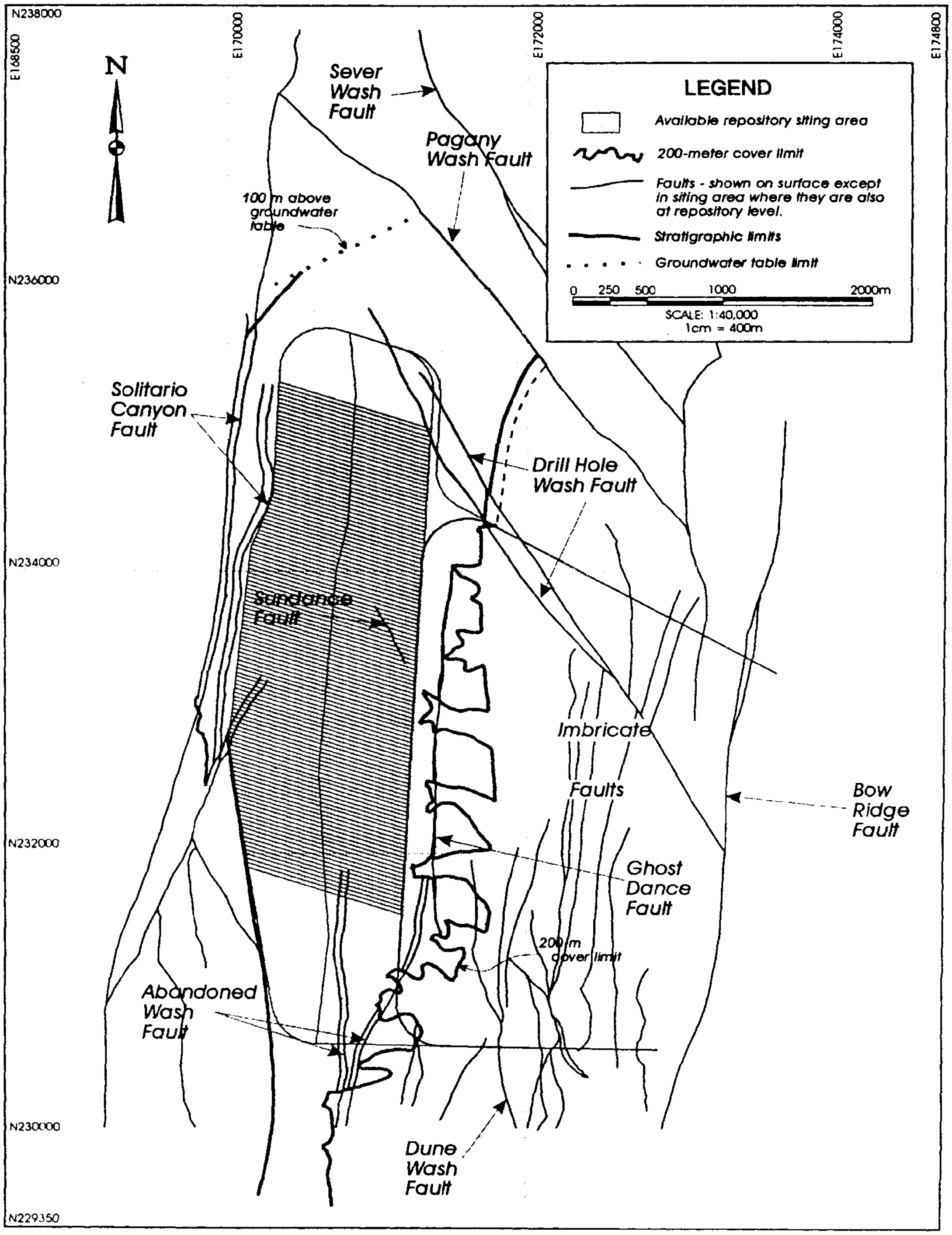


Figure 7-30. Repository Layout for the VA Reference Design (DOE98)

design parameters. The location of the repository within Yucca Mountain is shown in cross section in Figure 7-31.

The VA plan for functions and layout of the North Portal facilities is shown in Figure 7-32. Plans for South Portal operations and facilities are still under development and were not addressed in the VA.

Because of their initial high heat and radiation emissions, emplacement of the waste packages will be done remotely. As previously noted, the VA design temperature limit for the drifts is 200 ^{0}C; radiation field levels at the surface of the packages would be on the order of 35-60 rem/hour. A perspective view of the VA design concept for the emplacement transfer dock is shown in Figure 7-33. Design considerations include recovery from off-normal conditions.

7.2.2.2 Waste Package Design

Waste package designs will be tailored to the characteristics of the waste type (commercial spent PWR and BWR fuel; U.S. Navy spent fuel; other DOE-originated spent fuel; vitrified high-level waste; and immobilized surplus plutonium from nuclear weapons). The dominant types of waste packages in the repository will be those for commercial spent PWR and BWR fuel; in the VA reference design, there would be about 7,600 commercial spent fuel packages, two-thirds of which would contain PWR spent fuel and one-third BWR spent fuel. Most of the PWR packages would contain 21 spent fuel assemblies; the BWR packages would contain 44 assemblies (the BWR assemblies are about half the size of the PWR assemblies). Both types of waste packages contain about 10 MTHM.

The reference waste package design used in the Viability Assessment for the 21-PWR container is shown in Figure 7-33 (the BWR package is similar), and the design concept for the defense high-level waste container is shown in Figure 7-34. A key feature of the designs is use of two materials to form the walls of the package. The outer material, designated as a Corrosion Allowance Material (CAM), is A 516 carbon steel. The inner material, designated as a Corrosion Resistant Material (CRM), is a high-nickel alloy, Alloy 22, which is highly resistant to corrosion. The CAM is intended principally to provide strength and radiation shielding for the package; the CRM is intended to serve as the principal barrier to contact of water with the waste form within the package.

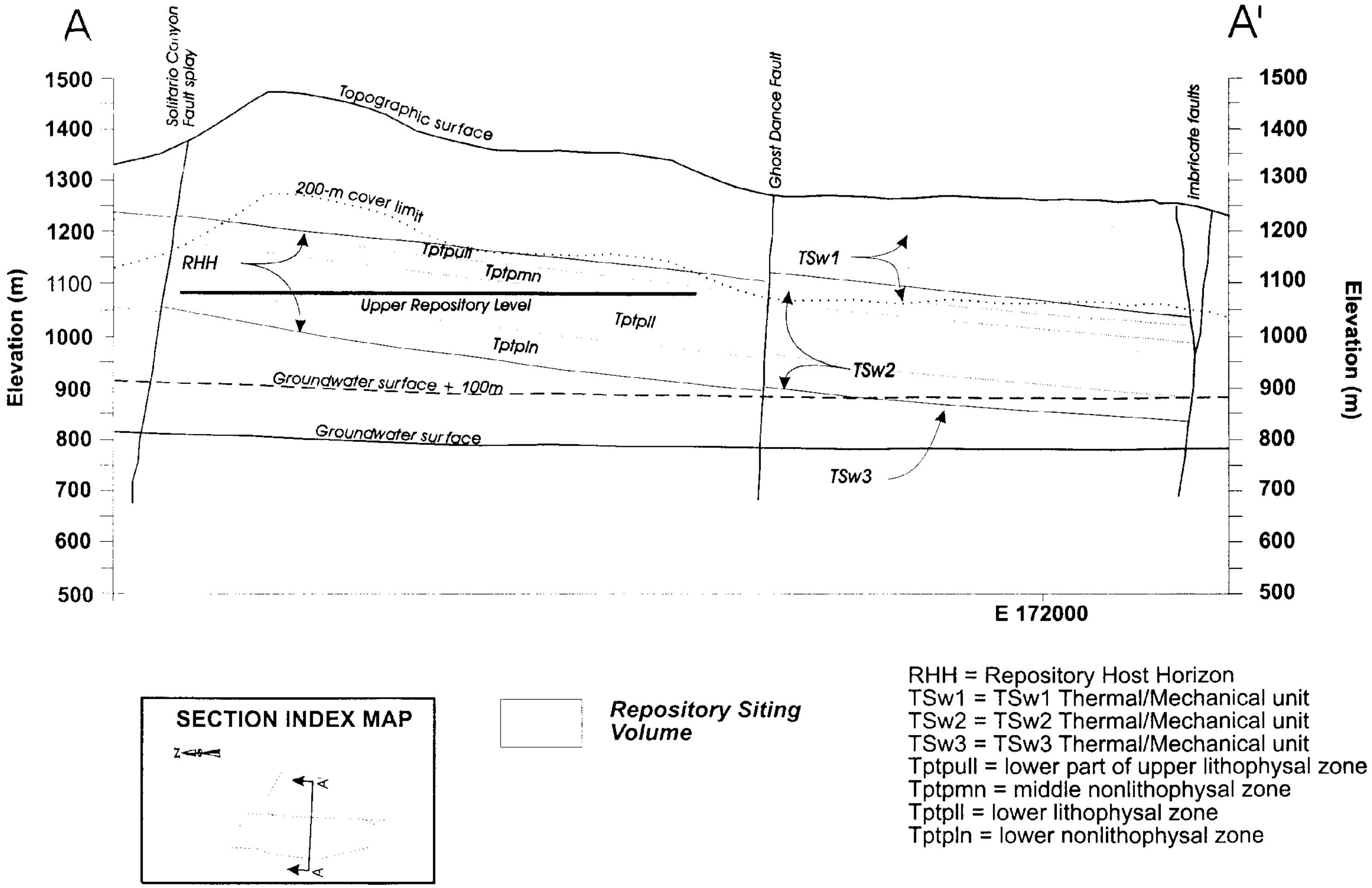


Figure 7-31. Repository Location Within Yucca Mountain (DOE98)

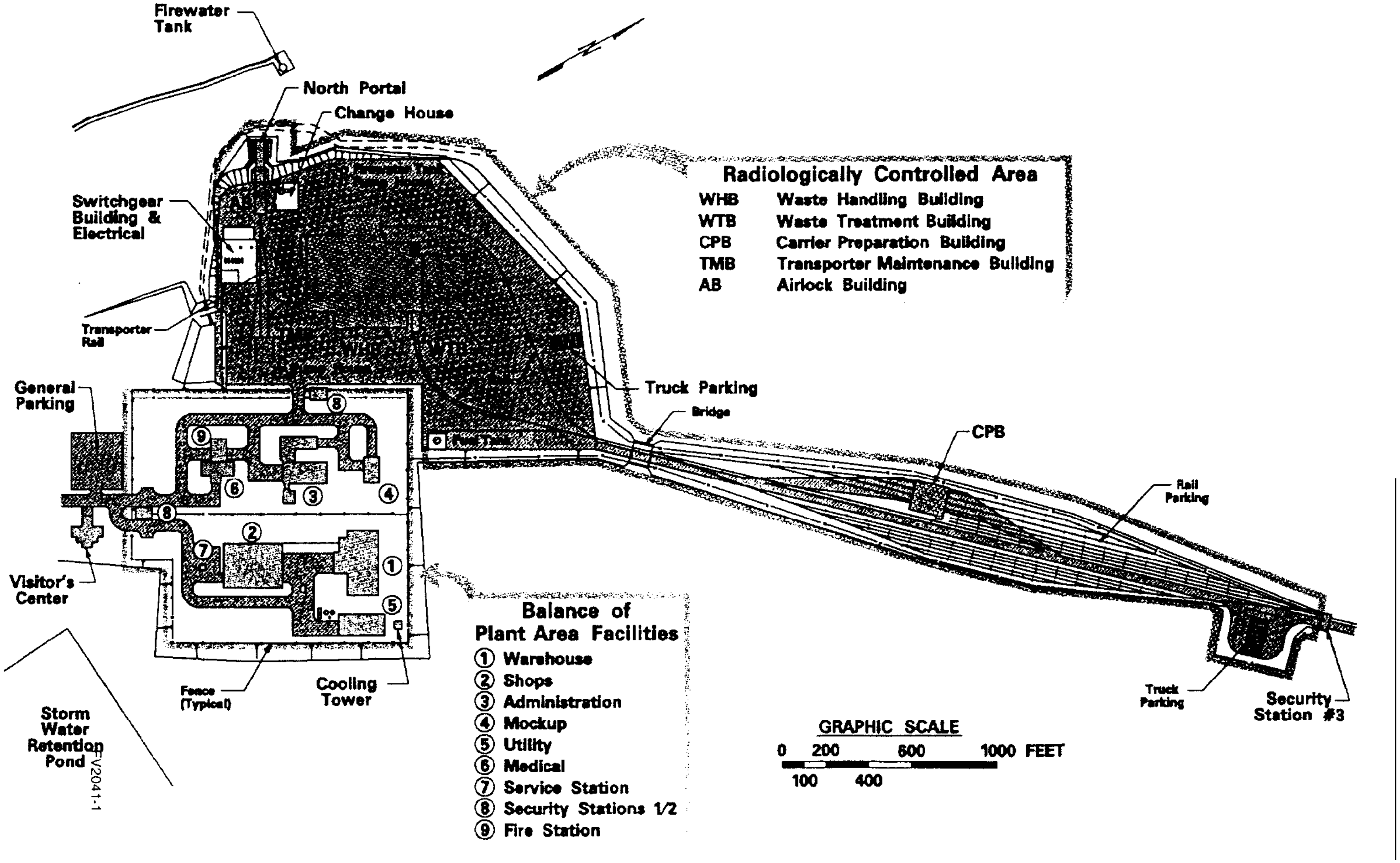


Figure 7-32. North Portal Facilities Layout for the VA Reference Design (DOE98)

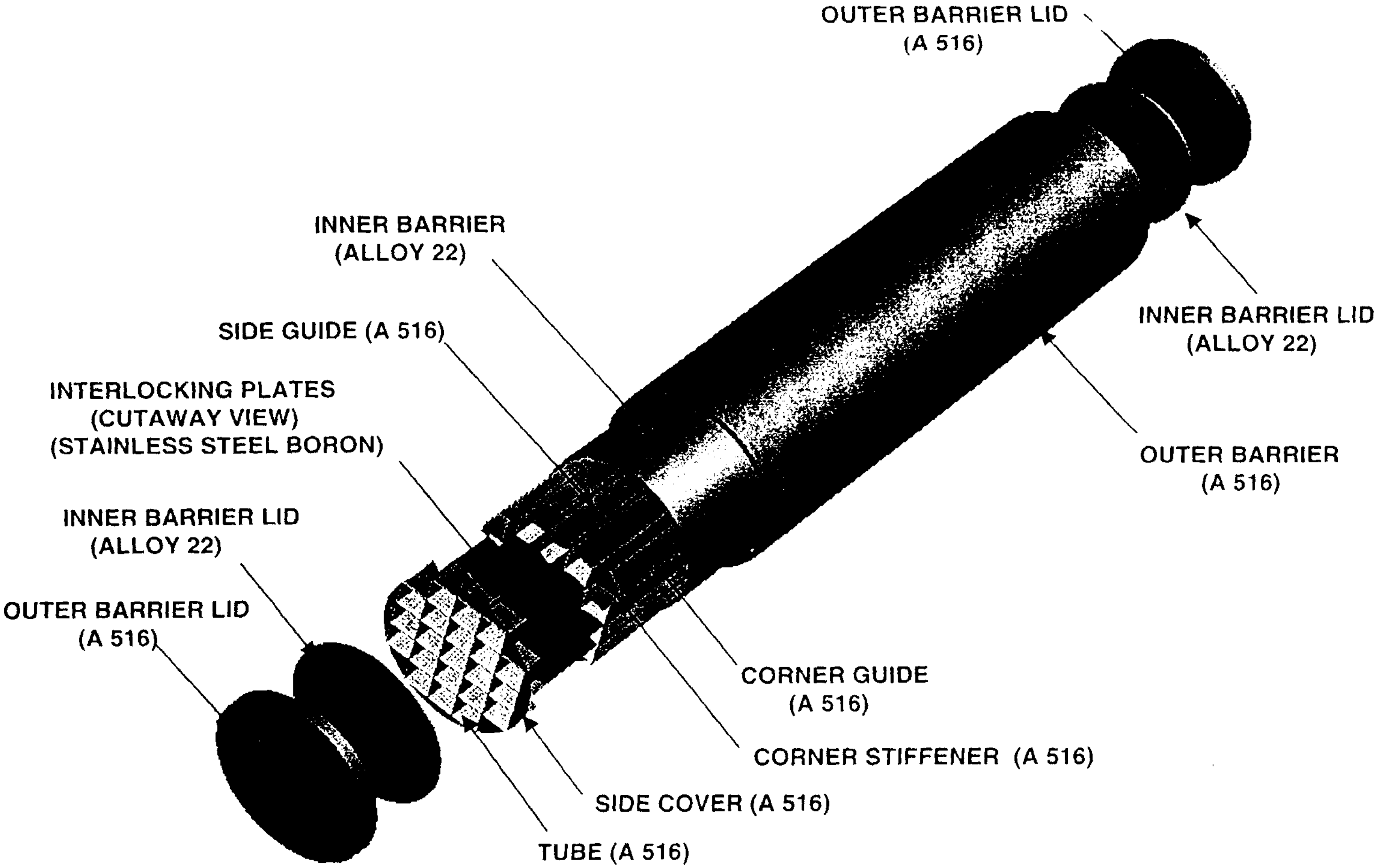


Figure 7-33. 21-PWR Waste Package Design for the VA Reference Design (DOE98)

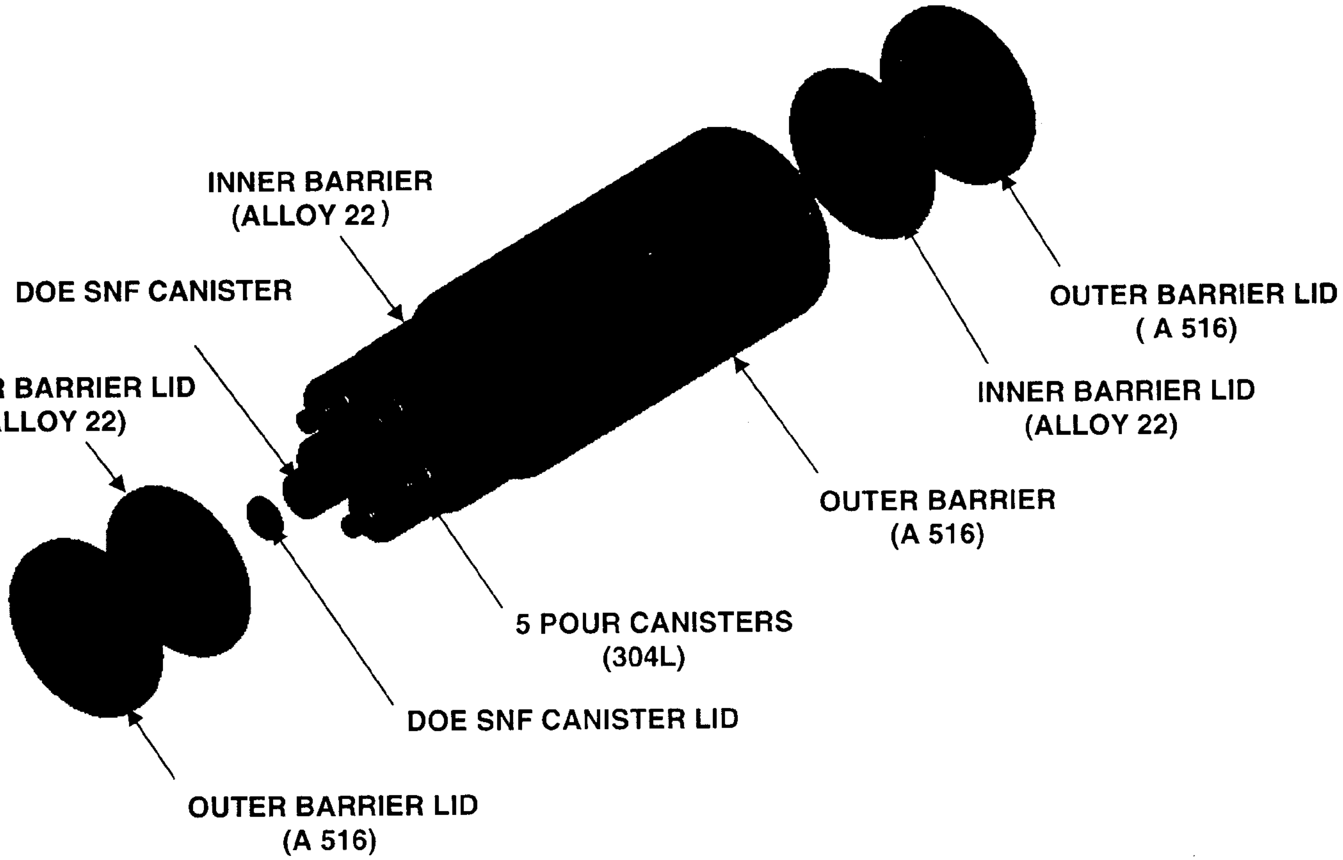


Figure 7-34. Defense HLW Package Design for the VA Reference Design (DOE98)

In the VA reference design, the waste packages were emplaced horizontally on concrete inverts in excavated drifts that were 5.5 m in diameter and lined with concrete. A cross section diagram of this reference design is shown in Figure 7-35. The drifts were spaced 28 m apart and the waste packages were spaced about 19 m apart in the drifts. Under this design concept, each waste package acts as a point source of heat emissions for repository performance evaluation purposes. An alternative design concept is to emplace the packages so that they touch each other end-to-end, in which case the performance evaluations treat the packages as a line source of heat emissions.

The VA also considered other engineered design concepts that were not included in the VA reference design. These design options included use of drip shields to aid in delaying and deflecting water from contact with the waste package, use of backfill, use of ceramic coatings on the waste packages, and use of waste package designs with the CRM on the outside or with use of two CRM materials. After the VA report was issued, the DOE began detailed evaluation of alternative designs with the objective of selecting design features that would be used in the Site Recommendation (SR) and the License Application (LA) if the Yucca Mountain site is found to be a suitable location for disposal. The design that will potentially be used in the SR and the LA is discussed in Section 7.2.2.5.

7.2.2.3 Thermal Management Strategy

Thermal management strategy is concerned with using the heat emitted by decay of the radioactive isotopes in the waste to control the temperature and the temperature gradients in and around the repository, thereby controlling or affecting access of water to the repository, contact of water with the waste packages, and the timing and rate of corrosion or degradation of the waste packages and other components of the engineered barrier system.

The thermal management strategy used for the VA was to impose a high heat load on the rocks surrounding the drifts so that water contained in the pore spaces would boil and be driven away from the drifts for as long as possible before the waste package heat emissions are too low to sustain this phenomenon. The heat load selected for the VA reference design was 85 MTU/acre, which was estimated to sustain temperatures at levels which would vaporize the percolation water for about 2,000 years (DOE98, Vol. 3, Figure 3-14).

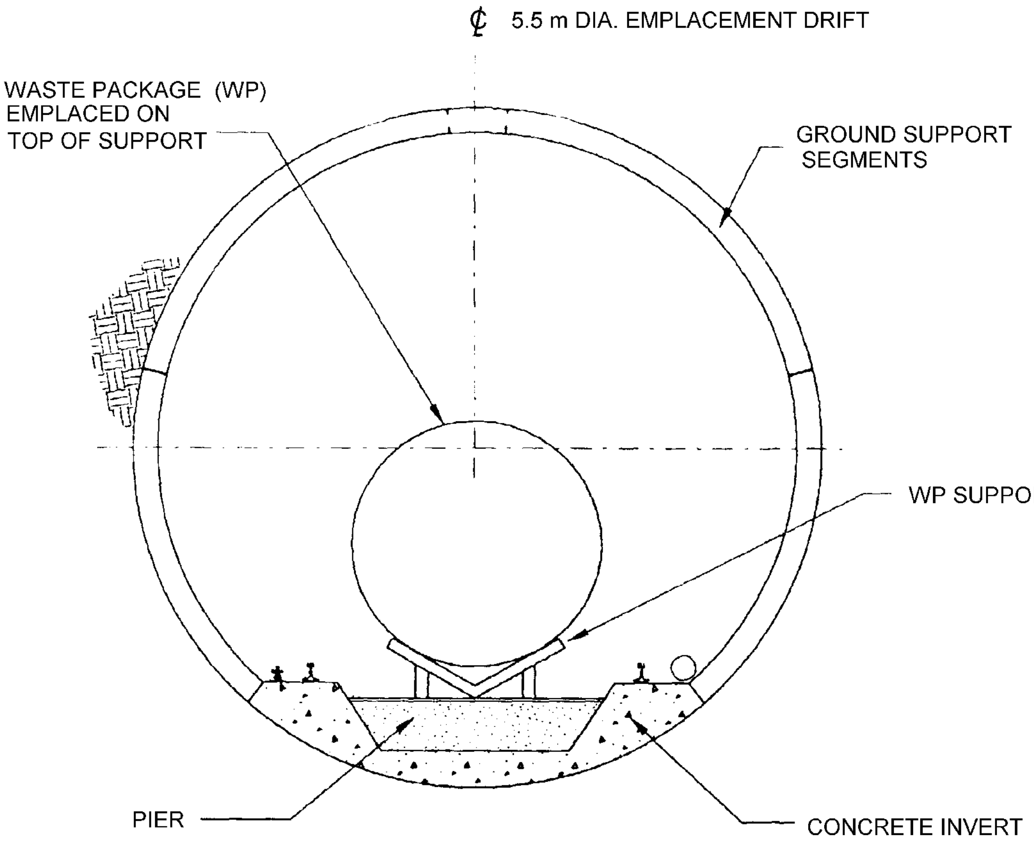


Figure 7-35. Drift Cross-Section for the VA Reference Design (DOE98)

High thermal loading of the geohydrologic regime surrounding the drifts has potential to produce a variety of effects on and within the regime, including opening or closure of fractures, mineralization, and changes in the composition of solid and dissolved species in the percolation water. The occurrence of such phenomena, and the impacts on long-term performance of the repository, are highly uncertain and will be difficult to model reliably for repository performance evaluations. These effcets could lessen or improve repository performance. The geohydrologic regime would undergo a temperature transient in which the temperatures near the drifts would peak at about 150 ^{0}C a few tens of years after emplacement, and would not return to pre-disposal ambient conditions for about 100,000 years. However, the temperature will have decayed to levels where liquid water can impinge on the waste packages in no more than 2,000 years.

The Electric Power Research Institute has provided comprehensive analyses and discussions of these complex issues and has developed models to characterize water/package contacts for alternative engineered designs and geohydrologic regime characteristics (EPR96). Their analyses demonstrate the wide range of conditions that can exist in the repository, and they also demonstrate the dependence of performance on interactions between the heat transfer regime, the hydrologic regime and repository thermal loading. They developed a five-dimensional matrix of scenarios and packages-wetted fractions which "...provides a method for capturing the correlations among heat transfer, water flow, waste package performance, and radionuclide migration in a performance assessment model." DOE and EPRI performance assessment methods and results are discussed in Section 7.3.

7.2.2.4 Data Sources

Characterization of the Yucca Mountain site has spanned more than 20 years to date. Both surface-based and underground investigations have been and are being performed to characterize the natural features of a repository at the site.

Surface-based studies have included mapping of geological structures; monitoring of seismic activity; use of gravitational, magnetic, and other non-invasive methods to infer geologic characteristics at depth; monitoring of current weather and climate conditions; collection of data to characterize past climates; heating of a large block of rock to determine the effects of heat on hydrologic and geochemical properties; and drilling of numerous boreholes to obtain data on geologic and hydrologic conditions at depth. Several hundred deep and shallow boreholes have been drilled at the proposed repository site and within the region.

Underground data have been obtained from tunnels excavated specifically to obtain in-situ data at the proposed repository horizon. The Exploratory Studies Facility (ESF), which is a north-south tunnel 8 m in diameter and 7.9 km in length and parallels what would be the eastern boundary of the repository and terminates at the North and South portals (see Figure 7-30). The Cross-Drift is an east-west tunnel which was excavated at a depth approximately 17 m above the proposed depth of the waste emplacement drifts and at about the mid-point of the north-south axis of the proposed repository. The surfaces of both of these tunnels have been mapped to obtain data on the geologic units, faults, and fractures at the repository horizon.

Alcoves and niches have been constructed at various locations along these tunnels to serve as facilities for a variety of experiments. Phenomena and physical properties being characterized include water flow characteristics in the unsaturated zone; drift-scale seepage; effects of high precipitation rates on flow; effects of heating on rock characteristics; fracture mineralization; characteristics of small-scale fractures; and the presence and characteristics of fluid inclusions.

In addition to these site characterization activities at the repository horizon, other data acquisition activities are in process. These include:

- Experiments are being performed in the tunnel facilities and at the Sundance fault zone and the Drillhole Wash fault zone to extend the data base of "bomb-pulse" Cl-36. This isotope can serve as a tracer to characterize the existence and characteristics of potential "fast paths" for water and radionuclide transport through the unsaturated zone.

- Pilot scale tests of backfill and drip shield performance are being conducted.

- The Nye County drilling program is providing data on the geologic and hydrologic characteristics of the alluvial deposits in the vicinity of Lathrop Wells. These data will be used to refine or revise the saturated zone flow and transport models.

- A multi-phase, multi-purpose test program concerning radionuclide transport in the unsaturated zone is being conducted at Busted Butte. Phases I and II are currently underway; Phase III of the program would be conducted as part of the performance confirmation program, i.e., after licensing if the site is approved for disposal.

The site data acquisition programs are augmented with laboratory programs to obtain other types of data. An extensive program to obtain corrosion data for candidate waste package materials is underway, involving a variety of corrosion environments and conditions expected potentially to exist in the repository. Laboratory investigations also use rock samples to characterize chemical, mechanical, and hydrologic properties of the geologic structures. Laboratory measurements also characterize radionuclide solubilities and sorption properties using water with chemical compositions expected to be characteristic of the repository.

These data acquisition activities have two broad purposes: to assure an adequate data base for licensing reviews if the site is approved for disposal, and to reduce reliance on the results of formal expert elicitations as a basis for performance models and performance parameter values.

To establish values for parameters used in the Viability Assessment, the DOE made extensive use of recommendations produced from formal expert elicitations conducted in accordance with guidelines established by the NRC. Process models subjected to expert elicitation included unsaturated zone flow, near-field environment, waste package degradation, waste form alteration and radionuclide mobilization, saturated zone flow and transport, probabilistic volcanic hazard assessment, and probabilistic seismic hazard assessment (DOE98, Vol. 3, Table 2-1). Reviewers of the VA, including the NRC, noted that the data base would have to be improved for a License Application, so that there would be less reliance on expert opinion. Present activities are intended to produce a data base that will be a sufficient foundation for performance models and parameter values to be included in the License Application.

7.2.2.5 Alternative Repository Design Concepts Under Consideration

The DOE considered the repository design concept used in the Viability Assessment to be a snapshot in time of the design evolution process. Within the VA documentation, the DOE identified, and provided preliminary characterizations of, alternative design features not included in the VA reference design. These included drip shields, backfill, alternative waste package wall materials, ceramic coatings on the waste packages, alternative thermal loadings, and alternative waste package emplacement configurations. The intent of these additional changes is to improve the performance of the engineered barrier system or reduce uncertainities in assessing its performance. Since issuance of the VA report in December 1998, the DOE has identified and characterized six alternative engineered repository designs incorporating these options (DOE99). As outlined below, one of these Enhanced Design Alternatives (EDA) has been selected to be the reference design concept for the Site Recommendation. If considered necessary, further evolution of the design may occur for the License Application if the site is approved for disposal.

The EDAs considered had common and variable features. Common features include use of drip shields; use of carbon steel ground support, use of a steel invert with granular ballast, instead of the concrete used in the VA reference design; use of a drift diameter of 5.5 m; use of pre-closure forced ventilation; and emplacement of 70,000 MTHM of radioactive wastes.

Design features that varied for the EDAs considered were the thermal loading and temperature objectives; use of backfill; selection of waste package wall materials; use of thermal blending to even out waste package heat emissions; drift spacing; waste package spacing; and repository location within the characterized area. Constraints imposed on the options were to maintain the temperature of cladding on commercial spent nuclear fuel at less than 350 ^{0}C; allow personnel access for off-normal events; and allow repository closure 50 or more years after start of waste emplacement. The thermal goals for the EDA options, which influence many design features, were:

- EDA I: Maintain drift wall temperature below boiling
- EDA II: Keep centers of pillars between drifts below boiling
- EDA III: Cool waste package surface to 80 ^{0}C before relative humidity reaches 90%
- EDA IV and V: Keep drifts dry for thousands of years

The design parameters for the EDAs considered are shown in Table 7-7. Note that EDA III includes two options for the waste package wall materials.

Analyses of these options produced the results shown in Table 7-8. Comparison of these results produced a recommendation by the M&O contractor to the DOE, which was accepted, that EDA II be used as the initial, reference design for the Site Recommendation. Principal features of the EDA II design are compared with those of the VA reference design in Table 7-9.

In comparison with the VA reference design, the EDA II design is expected to reduce uncertainties that could be of concern during licensing reviews. Uncertainties that are expected to be less significant as licensing issues are those concerning coupled thermal, hydrologic, mechanical, and chemical processes; alteration of the natural system as a result of the heat load on the geologic units surrounding the drifts; processes and phenomena that affect radionuclide transport; and potential for localized corrosion of waste package wall materials. The EDA II design is also expected to provide improved defense-in-depth and overall performance. One of the principal features of the design is that the time-temperature history of the waste packages is expected to avoid conditions in which the Alloy 22 outer wall would be vulnerable to crevice corrosion.

Repository performance assessment models and parameter values (see Section 7.3) will be revised from those used in the VA in accord with the EDA II design parameters and the information emerging from the data acquisition program described in Section 7.2.2.4. One of the principal performance assessment issues for the Site Recommendation, using the EDA II design,

DESIGN ELEMENT	EDA I	EDA II	EDA III	EDA IV	EDA V
Thermal Goals					
• Cladding	350°C	350°C	350°C	350°C	350°C
• Waste package surface			Cools to 80°C before relative humidity reaches 90%		
• Drift wall	96°C	200°C	200°C	200°C	225°C
• Drift environment				Keep drifts dry for thousands of years	Keep drifts dry for several thousand years
• Pillar temperatures		Keep centers of pillars below boiling (96°C)			
• Other goals				Limit gamma dose at waste package surface to 200 mrem/hr	
Areal Mass Loading (MTHM/acre)	45	60	85	85	150
Area (acres) for 70,000 MTHM	1,400	1,050	740	740	420
Line/Point Load	Point	Line	Line	Line	Line
Waste Package Size (PWR)	12	21	21	21	21
Drift Diameter (m)	5.5	5.5	5.5	5.5	5.5
Drift Spacing (m)	43	81	56	56	32
Preclosure Ventilation	50 years @ 2 to10 m^3/s	50 years @ 2 to 10 m^3/s	50 years @ 2 to10 m^3/s	50 years @ 2 to10 m^3/s	50 years @ 2 to 10 m^3/s
Waste package heat output at emplacement Maximum Average (PWR waste package) (CRWMS M&O 1999bb)	20% blending used to reduce maximum 6.7 kW 5.6 kW	20% blending used to reduce maximum 11.8 kW 9.8 kW	Limited blending 18.0 kW 9.5 kW for PWR	Limited blending 18.0 kW 9.5 kW	20% blending used to reduce maximum 11.8 kW 9.8 kW
Waste Package Material	2-cm Alloy-22 over 5-cm stainless steel	2-cm Alloy-22 over 5-cm stainless steel	a) 2-cm Alloy-22 over 5-cm stainless steel b) 2-cm Alloy-22 over 1.5-cm Ti-7 over 4-cm stainless steel	30-cm carbon steel	2-cm Alloy-22 over 5-cm stainless steel
Fillers	No	No	No	Integral filler	No
Backfill	No	Yes	No	Yes	No
Drip Shield	Yes	Yes	Yes	Yes	Yes
Total Waste Packages	15,903	10,039	10,213	10,213	10,039

Table 7-7. Design Parameters for the Enhanced Design Alternatives (DOE99)

Performance Categories		EDA I	EDA II	EDAs IIIa/IIIb	EDA IV	EDA V
Performance Factors	Margin	2,500	3,550	1,500	180,000	1,250
	Time to 25 mrem	290,000 years	310,000 years	290,000/ 310,000 years	100,000 years	300,000 years
	Peak Annual Dose	85 mrem	85 mrem	215/100 mrem	1,200 mrem	200 mrem
Licensing Probability/Safety Factors	Rock Temperatures	Always below 96°C	>96°C several m's into drift for hundreds of yrs.	>96°C across most of repository	>96°C across most of repository	>96°C across essentially all of repository
	Waste Package Corrosion	Does not enter aggressive corrosion range	Does not enter aggressive corrosion range	Some WPs in aggressive corr. range for 1000s of years	Humid air corrosion of WPs begins as early as 100 years	Some WPs in aggressive corrosion range >10,000 years
Construction, Operations, and Maintenance Factors	Number of Waste Packages	15,903	10,039	10,213	10,213	10,039
	Length of Emplacement Drifts	132 km	54 km	55 km	60 km	54 km
	Key Construction, Operations, and Maintenance Issues	Operational impacts of more packages and longer drifts; blending	Blending; emplacement of backfill	Fabrication of dual corrosion-resistant material package in IIIb	Fabrication, welding, and handling thick WPs; empl. of backfill	Blending
Flexibility Factors	Emplacement area for 70,000 MTHM	1,400 acres	1,050 acres	740 acres	740 acres	420 acres
	Ability to Change to Lower Temperature	N/A	Requires longer ventilation	Requires changes in drift spacing	High temp. integral to WP performance	Requires changes in drift spacing
	Ability to Change to Higher Temperature	Requires development of larger packages and coupled models for PA	Requires devel. of coupled models for PA	N/A	N/A	N/A
Cost	Repository Life Cycle Cost	$25.1 billion	$20.6 billion	$20.1 billion/ $21.3 billion	$21.7 billion	$20.0 billion
	Net Present Value	$13.4 billion	$11.0 billion	$10.7 billion/ $11.4 billion	$11.3 billion	$10.8 billion

Table 7-8. Principal Results of Enhanced Design Alternative Analyses (DOE99)

Design Characteristics	EDA II	Viability Assessment Design
Areal Mass Loading	60 MTU/acre	85 MTU/acre
Drift Spacing	81m	28 m
Drift Diameter	5.5 m	5.5 m
Total Length of Emplacement Drifts	54 km	107 km
Ground Support	Steel	Concrete lining
Invert	Steel with sand or gravel ballast	Concrete
Number of Waste Packages	10,039	10,500
Waste Package Material	2-cm Alloy 22 over 5 cm stainless steel 316L	10 cm carbon steel over 2 cm Alloy-22
Maximum Waste Package Capacity	21PWR assemblies	21 PWR assemblies
Peak Waste Package Power (blending)	20% above average PWR waste package power	95% above average PWR waste package power
Drip Shield	2 cm Ti-7	none
Backfill	Yes	none
Preclosure Period	50 years *	50 years
Preclosure Ventilation Rate	2 to 10 cubic m /s	0.1 cubic m/s

Table 7-9. Comparison of EDA II and Viability Assessment Design Features (DOE99)

will be the potential for early ("juvenile") waste package failures that allow seepage water to enter the package, mobilize radionuclides, and transport them to the environment. For EDA II design conditions, waste package failures would not be expected for 100,000 years or more, except as a result of manufacturing or handling defects. One of the principal potential manufacturing defects is imperfect welds, characteristics of which have been under investigation by the NRC for over 20 years in connection with potential for failures in nuclear power reactors. The DOE has developed the RR-PRODIGAL code, based on research results, to model flaw occurrences in welds, and is developing probability and consequence estimates for flaw types not addressed by this code. These methods for estimating potential for juvenile waste package failures in a repository design based on the EDA II design features will be an important element of performance assessments for the Site Recommendation and the License Application.

7.3 REPOSITORY SYSTEM PERFORMANCE ASSESSMENTS

The post-closure safety performance of a geologic repository for radioactive wastes is evaluated using a Total System Performance Assessment (TSPA). A TSPA involves use of models of the physical characteristics of the repository system, in a suite of linked computer codes, to forecast the longterm performance of the system in terms of factors, such as waste package degradation, which lead to release of radionuclides from the repository and their transport in the environment. The TSPA tskes into consideration the features, processes, and events that can affect radionuclide release and transport.

Features that affect performance include factors such as the corrosion rate of the waste package. Processes that affect performance include factors such as the rate at which water seeps into the drifts, and events important to performance include factors such as earthquakes, volcanic eruptions, and intrusion of the repository by human action. A TSPA takes all of these factors into account, consistent with the engineered and natural features of the repository system.

Evaluations of total system performance for potential repositories at Yucca Mountain have been performed by DOE, EPRI, and the NRC. As discussed below, the DOE has performed a series of TSPA evaluations, for purposes of helping to guide design evolution and site characterization work. EPRI has also performed a series of independent evaluations, using models and methods significantly different from those of the DOE. The NRC has performed evaluations to demonstrate their capability to perform licensing reviews of TSPA results that would be provided by the DOE in a License Application.

DOE's historic TSPA efforts are discussed in Section 7.3.1, and the TSPA-VA is described in Section 7.3.2. NRC's performance assessments are discussed in Section 7.4, and EPRI's efforts are described in Section 7.5. Results of recent assessments by DOE, NRC, and EPRI are compared in Section 7.6.

7.3.1 DOE's Historic Performance Assessments

DOE's TSPA process began with the PACE-90 project (DOE91). PACE-90 was not a total-system evaluation; it focused on numerical modeling of the hydrologic regime and simulated ground-water flow and aqueous transport of radionuclides. Because data were sparse at the time, models were simplistic and many performance factors were not considered. The PACE-90 analyses served to demonstrate the TSPA concept, and it laid the foundation for future TSPA evaluations.

The DOE subsequently has conducted TSPA evaluations in 1991 (DOE92), 1993 (DOE94a, DOE94b), 1995 (DOE95b), and, most recently, for the Viability Assessment (TSPA-VA, DOE98). Each assessment built on the insights and results of prior assessments, and on the evolving data base and design concepts. Each successive TSPA evaluation added details and features to the models and parameter values in accord with progress enabled by the evolving information base.

During the period of evolution of TSPA analyses to date, the regulatory basis for standards, against which repository performance is to be evaluated, was revised. As discussed in Section 1.2 of this BID, the Energy Policy Act of 1992 directed the EPA to develop site-specific radiation protection standards for Yucca Mountain, consistent with the findings and recommendations of the National Academy of Sciences. Accordingly, the Agency has developed the proposed 40 CFR Part 197 regulations supported by this BID. These standards propose dose limits as a basis for radiation protection. The prior standards, contained in 40 CFR Part 191, also included individual protection requirements (Section 191,15; see Section 1.4.4 of this BID) but established cumulative release of radionuclides across an accessible environment boundary as the basis for regulatory compliance.

Because of the difference in the type of radiation protection standards, the results of the TSPA-VA analyses are expressed differently from those of prior analyses. Consistent with a dose-limit standard, the TSPA-VA results are expressed as potential doses to receptors, for time periods up to one million years. In contrast, results for the TSPA 1991, 1993, and 1995 analyses were expressed in terms of a Complementary Cumulative Distribution Function (CCDF), which is an appropriate representation of results for comparison with the cumulative release standards established in the 40 CFR Part 191 regulations.

Key features of DOE's TSPA evaluations in 1991, 1993, and 1995 are summarized below.

TSPA-91

The TSPA-91 analyses were designed to develop the framework for probabilistic total-system performance characterizations. They built upon the PACE-90 analyses by modeling nominal conditions and disturbances from basaltic volcanism, human intrusion, and climate change. They included the first set of stochastic analyses, in which hydrologic parameters were represented by probability distribution functions based on site and analog data. Gaseous flow of C-14 was modeled, the saturated zone was modeled for the first time, and results were, for the first time, obtained at the accessible environment boundary as defined by EPA's 40 CFR Part 191 regulations. Future changes in climate were represented by a range of percolation flux values at the repository horizon.

TSPA-93

The TSPA-93 analyses were aimed at providing guidance for site characterization work and engineered designs. In comparison with TSPA-91, the models of physical features and processes were more sophisticated and the data base for selection of models and parameter values was larger. Important features of the analyses included:

- A three-dimensional stratigraphy for the unsaturated zone which was based on site data.
- A saturated zone model in which each geohydrologic unit was discretely modeled.
- Assessment of the effect of thermal loading (at levels of 57 and 114 kW/acre) on performance.
- Waste package failure models which included aqueous and dry oxidation corrosion, and waste form degradation models which included dissolution and oxidation.

- Consideration of two types of waste packages: the thin-walled, small-capacity containers emplaced in boreholes, as envisioned in the Site Characterization Plan (DOE88), and, for the first time, the large-capacity packages emplaced horizontally in drifts.

In anticipation of changes in regulations as a result of requirements of the Energy Policy Act of 1992, the TSPA-93 analyses included assessments of potential doses to humans as well as results based on cumulative radionuclide releases from the repository, consistent with the 40 CFR Part 191 disposal standards. These results were illustrative, and were not intended in any way to represent the actual potential performance of a repository at the Yucca Mountain site. At that time the observation was made that more-representative models and data were needed to improve the realism of the analyses.

TSPA-95

As a result of studies of design options and guidance for site characterization work provided by the results of the TSPA-93 analyses, the data basis for the TSAP-95 evaluations was significantly improved over that which had previously been available. TSPA-95 sought to be as realistic as possible on the basis of available information and the evolved repository and waste package designs.

The focus of the TSPA-95 analyses was those components of the system that had been determined by prior analyses to be most important to the waste isolation capability of the repository. Emphasis was therefore placed on the engineered components and the near-field environment in which they would reside. In comparison with TSPA-93, the TSPA-95 evaluations used improved and more realistic models of the drift-scale thermal-hydrologic environment and also of waste package degradation. Models describing the transport of water in the near-field engineered barrier system were included, and flow in the unsaturated zone was modeled. Disruptive events and gaseous release were not considered because they had been shown in TSPA-93 not to be significant to overall performance.

Some of the models and parameter values used in TSPA-95 were based on judgments derived from expert elicitations, because experimental data were limited or non-existent. Data acquisition programs, such as corrosion testing and site characterization, are continuing and are expected in the future to enable replacement of expert elicitation judgments with experimental data.

The TSPA-95 analyses evaluated waste package lifetime, the peak EBS release rate, the cumulative release at the boundary of the accessible environment, assumed to be 5 km from the repository, and the peak dose rate, at 10,000 and one million years, to the maximally exposed individual located at the boundary of the accessible environment. Evaluations were done using alternative models and a range of alternative values for performance parameters, such as the repository thermal loading, infiltration rate, and climate change. The DOE noted that, at the time TSPA-95 was conducted, there were no documented models with substantiation adequate for use with confidence in performance assessments. Never-the-less, TSPA-95 laid the foundation for future TSPA evaluations using improved models and an expanded data base.

According to the DOE, the principal findings derived from the TSPA-95 analyses can be summarized as follows:

- Percolation flux at the repository horizon (and attendant seepage into the drifts) is a dominant factor in repository system performance. This flux affects the potential for water to drip into the drifts, the magnitude of radionuclide release from a penetrated waste package, and the movement of radionuclides through the unsaturated zone.

- Radionuclides that dominate dose potential for the 10,000-year time frame are Tc-99 and I-129. Long-term doses are dominated by Np-237.

- Assumptions about dispersion and dilution in the UZ and SZ will have a strong effect on peak dose rates.

- Excluding juvenile waste package failures from manufacturing defects, if waste packages using the TSPA-95 design are not penetrated as a result of highly aggressive corrosion conditions such as crevice corrosion, the EBS can by itself provide complete containment of radionuclides for 10,000 years. Similarly, if the percolation flux is low the natural-barriers system will provide complete isolation for 10,000 years.

7.3.2 DOE's TSPA for the Viability Assessment (TSPA-VA)

The TSPA-VA was part of the comprehensive assessment of the viability of the Yucca Mountain project that was mandated by Congress in the Energy and Water Appropriations Act of 1997. In comparison with prior TSPA efforts, the TSPA-VA was much more comprehensive and detailed. Some previously used models were revised; models of repository features that affect performance and had not been included in previous TSPA efforts were added to the computer code configuration; waste package design features were revised; and data that had been developed since TSPA-95 was prepared were used to provide details such as the spatial distribution of infiltration rates.

The discussion in this section of the BID is specific for the VA repository design, the TSPA-VA models and assumptions, and the data base used in the TSPA-VA. As noted by DOE in the VA report, the VA data base, reference design, and TSPA results constitute a step in an evolutionary process. Further design revisions and data additions are expected, leading to design features and TSPA methods and results for the Site Recommendation and for a License Application if the site is found to be a suitable location for disposal.

Comprehensive discussion of the TSPA-VA is included in this BID because it is the most recently available detailed information concerning DOE performance assessments for Yucca Mountain. Although revisions to TSPA-VA methods and results are expected, only limited information on future repository designs and TSPA methods is currently available. Documentation of the first draft of the TSPA for the Site Recommendation is currently planned to be available in July 2000; documentation of a revised TSPA-SR is currently planned for February 2001.

7.3.2.1 Repository Design Features for the TSPA-VA

Repository design concepts have evolved significantly over the years of site evaluation. As previously noted, for example, the design concept used in the Site Characterization Plan issued in 1988 was vertical emplacement of canisters with small capacities into the floors of the tunnels and with expected lifetimes on the order of 300-1,000 years. The basic concept used for the TSPA-VA was to emplace large, highly robust waste packages with design lifetimes on the order of tens of thousands of years horizontally in excavated drifts. This concept is similar to that used in TSPA-95, but the waste package wall materials were different.

This section summarizes the engineered features of the VA repository that are of importance to safety performance and TSPA results. In general, these are design features that are specifically selected to aid waste isolation by delaying and diminishing opportunities for water to enter the drifts, to contact the waste form, leach out radionuclides, and transport the radioactivity to the environment.

In the reference Engineered Barrier System (EBS) design that served as the basis for the TSPA-VA analyses, the principal design features that contributed to waste isolation were use of high waste package emplacement density so that repository temperatures would be high enough to boil water in the rocks and drive it away from the repository for as long as possible; use of a drift liner to help keep out seepage water for as long as the liner lasts; and use of a highly corrosion-resistant waste-package wall material which would be expected not to be penetrated by corrosion for very long periods of time. The TSPA-VA also characterized the potential performance of supplemental engineered features (use of backfill, drip shields over the waste packages, and ceramic coatings on the packages), but these features were not included in the VA reference design.

Assumptions That Provide the Basis for Design Parameter Values

Within the framework of the waste isolation strategy outlined above, assumptions were necessary as a basis for selecting design parameters. Key assumptions included the following:

- The Nuclear Waste Policy Act of 1982 limits the repository to a total capacity of 70,000 metric tonnes of uranium (MTU) as spent fuel or equivalent. The repository for the TSPA was assumed to contain 63,000 MTU of commercial spent fuel and 7,000 MTU equivalent of defense wastes, including vitrified high-level waste from defense production operations and spent fuel from naval reactors.

- Spent nuclear fuel assemblies from pressurized-water reactors will be, on average, 25.9 years out-of-reactor, with a 3.69 weight percent initial enrichment and a burnup value of 39.56 gigawatt-days per MTU. Spent fuel assemblies from boiling water reactors will be, on average, 27.2 years out-of-reactor, with 3.00 weight percent initial enrichment and a burnup value of 32.24 gigawatt-days per MTU.

- Commercial spent nuclear fuel (CSNF) will be emplaced in the repository in packages containing 21, 12, or 24 PWR assemblies per package and 44 BWR assemblies per package each containing about 10 MTHM. There will be a total of 7,642 CSNF packages in the repository. There will be a total of 2,858 packages of defense wastes, for a repository total of 10,500 waste packages.

- The surface facilities, subsurface facilities, and waste package designs will be based on a reference areal mass loading range of 80 to 100 MTU/acre.

- The temperature of the drift walls will be limited to no more than 200°C (392°F).

- The temperature of the CSNF fuel cladding will be limited to 350°C (662°F).
- The repository's western and eastern boundaries will be between the Solitario Canyon fault and the Ghost Dance fault

The reference repository and waste package designs that emerged from these and other assumptions important to safety for handling and emplacement operations are summarized below.

Repository Footprint

The repository layout that resulted from the assumptions concerning standoff from the faults, temperature limits, and the areal emplacement density is shown in Figure 7-30. The repository east-west width is about 1 km and the north-south length is about 3 km. The repository would be located at a depth about 300 m (1,000 feet) below the crest of the mountain and 300 m above the water table. The main emplacement drifts would be 5.5 meters (18 feet) in diameter; 104 drifts, totaling 107 km (67 miles) of length, would be excavated to emplace the 70,000 MTU of wastes. The drifts would be spaced 28 meters (90 feet) apart, and the extraction ratio (fraction of the volume excavated) for the emplacement region of the repository would be 19.6%.

Waste Package Emplacement Configuration

Given the assumptions about waste-package capacity, each package would be about 6 feet (2 meters) in diameter and about 6 meters (18 feet) long to accommodate the dimensions of the intact CSNF assemblies. Details of the package dimensions will vary because of variations in assembly dimensions.

A cross-section diagram of a typical waste package emplaced in a drift is shown in Figure 7-35. The package will be emplaced horizontally on steel V-shaped supports, which in turn are set on a concrete invert and pier. The drift is lined with concrete. The invert completes a concrete ring around the perimeter of the drift and also provides a roadbed for construction and emplacement operations.

Waste Package Design

A perspective diagram of the waste package design for disposal of 21 PWR spent fuel assemblies is shown in Figure 7-34. Packages for disposal of BWR spent fuel assemblies and for disposal of defense wastes are conceptually similar in design. As previously indicated, the packages for disposal of PWR and BWR spent fuel would be about 6 feet in diameter and 18 feet long. Packages for disposal of defense wastes would be about 6 feet in diameter and 10 feet long.

The design features of most importance to the TSPA-VA are the materials selected for the waste package walls, identified in Figure 7-34 as the inner and outer barriers. Each package has an inner barrier of Alloy 22, which is a high-nickel, corrosion-resistant alloy intended in the design to provide the principal barrier to penetration of water into the interior of the package. The outer barrier, which in the reference design is a 516 steel, is intended primarily to provide shielding and package strength. The reference design thickness of the outer barrier is 100 mm (4 inches); the inner barrier is 20 mm (0.7 inches) thick.

Design Options

Many other possible design concepts and parameter values are identified and discussed in some detail in the VA documentation (see, for example, Volume 2, Section 8 of DOE98). The options include alternative design features, such as use of drip shields or ceramic coatings to defer the time at which water can contact the waste package wall and begin to penetrate it, and alternative design strategies. Although not part of the VA reference design, the effects of backfill, drip shields, and ceramic coatings on repository performance were evaluated in the TSPA-VA.

Alternative strategies include use of a low emplacement density or long-term cooling before emplacement, either of which would reduce the areal thermal loading and would be intended to reduce performance issues and uncertainties arising from the high temperatures associated with the VA reference design. DOE is proceeding to characterize and evaluate some of the options, which might be implemented in the design for the Site Recommendation and the License Application if the site is found suitable for use for disposal.

7.3.2.2 TSPA Concepts and Methodology

This section presents an overview of TSPA concepts and methodologies that are the basis for DOE’s implementation of performance assessment in the TSPA-VA. As previously noted, the TSPA-VA is a snapshot in time of performance evaluation for the VA reference design, data base, and models that were available for the purpose. If the Yucca Mountain project proceeds to the stage of preparing a License Application for a repository at Yucca Mountain, the details of the TSPA for the application would likely be different from those of the TSPA-VA.

The basic TSPA principles used for the TSPA-VA have been adopted in radioactive waste disposal programs throughout the world as the means for forecasting the post-disposal performance of a repository. For any given repository natural setting and engineered design, the process involves five basic steps:

- Develop and screen scenarios of conditions and factors important to performance. Scenarios address features, processes, and events that can affect repository performance, such as average annual precipitation rates and changes therein.
- Develop analytical models to represent the factors important to performance. The models are usually implemented as computer codes
- Assign values to performance parameters in the models. Some parameters will be single-valued, such as the density of water at a given temperature; others will have uncertainty ranges because of inherent variability or lack of certain knowledge of the value.
- Implement the models by operating the computer codes
- Interpret and apply the results for purposes such as identification of additional data needs or assessment of compliance with regulatory standards

For a proposed repository at Yucca Mountain with its particular geohydrologic setting, DOE selected four basic performance strategy factors:

- Limit the potential for water to contact the waste packages
- Design the waste package for a long lifetime
- Seek a low rate of release from breached waste packages

- Seek radionuclide concentration reduction during transport through the environment to the location of the dose receptor

This strategy was implemented by identifying principal performance factors and components of the TSPA modeling configuration as shown in Table 7-10. As indicated in this table, the model components are aligned with the Key Technical Issues that NRC has identified as the basis for review of DOE's assessments of repository performance. Parameter values and subsystem models were developed for each of the 19 principal performance factors listed in Table 7-10.

Each of the performance factors listed in Table 7-10 can be characterized as a driver or an inhibitor of radionuclide release and transport. For example:

- Precipitation, infiltration, seepage, and dripping are drivers for radionuclide release that bring water to the waste packages

- Waste package humidity, temperature, and chemistry drive the rate of attack on the inner and outer waste package barriers

- The waste package wall is a principal inhibitor of radionuclide release; inhibition of release is also accomplished by the integrity of the spent fuel cladding, resistance to dissolution of the waste forms, and the limited solubility in water of Np-237

- Radionuclide mobility during transit from the repository to and through the environment is aided if the radionuclides are attached to colloids but inhibited if they become sorbed onto surfaces along the flow path

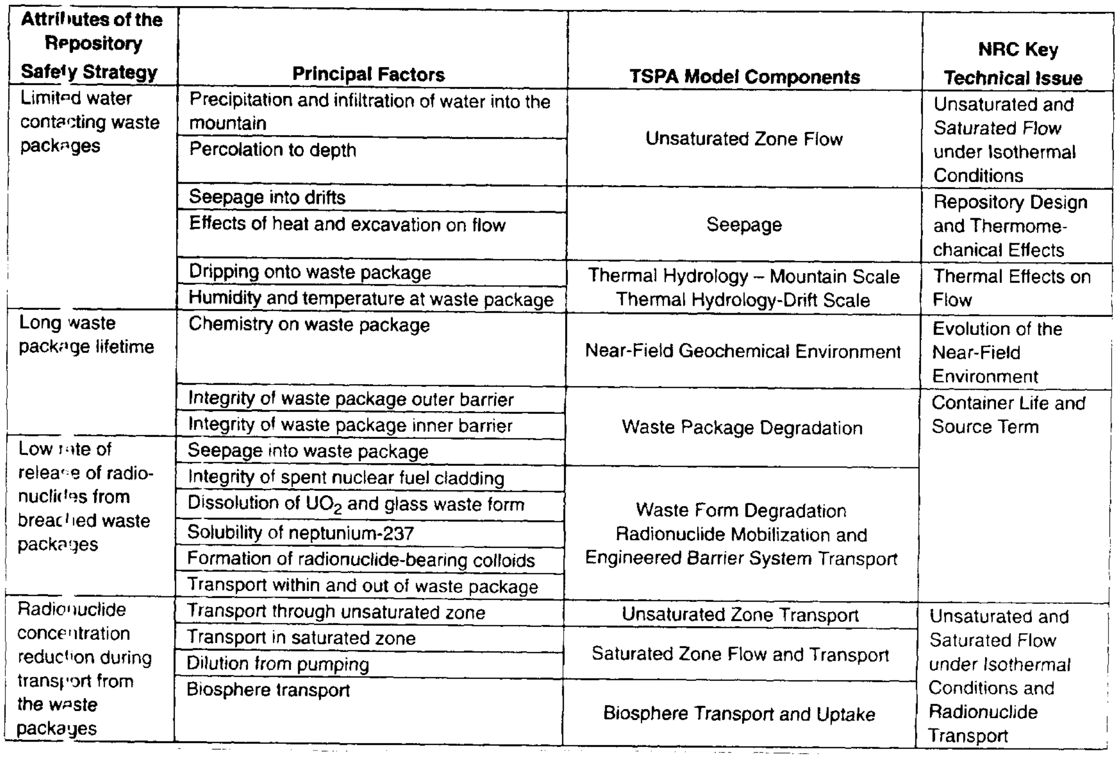
- Transport of radionuclide-bearing water from breached packages brings the radionuclides to the dose receptor location through pathways in the unsaturated and saturated zones

- Dilution during transit and pumping will reduce the radionuclide concentrations in water used by the dose receptor

- Biosphere transport will bring radionuclides into contact with the dose receptor in accord with his/her life style and practices

The specific characteristics of each of these drivers or inhibitors of radionuclide release and transport are represented in the parameters and models used in the TSPA.

Table 7-10. Principal Performance Factors for TSPA-VA Modeling (DOE98)



Attributes of the Repository Safety Strategy	Principal Factors	TSPA Model Components	NRC Key Technical Issue
Limited water contacting waste packages	Precipitation and infiltration of water into the mountain	Unsaturated Zone Flow	Unsaturated and Saturated Flow under Isothermal Conditions
	Percolation to depth		
	Seepage into drifts	Seepage	Repository Design and Thermomechanical Effects
	Effects of heat and excavation on flow		
	Dripping onto waste package	Thermal Hydrology – Mountain Scale Thermal Hydrology-Drift Scale	Thermal Effects on Flow
	Humidity and temperature at waste package		
Long waste package lifetime	Chemistry on waste package	Near-Field Geochemical Environment	Evolution of the Near-Field Environment
	Integrity of waste package outer barrier	Waste Package Degradation	Container Life and Source Term
	Integrity of waste package inner barrier		
Low rate of release of radionuclides from breached waste packages	Seepage into waste package		
	Integrity of spent nuclear fuel cladding	Waste Form Degradation Radionuclide Mobilization and Engineered Barrier System Transport	
	Dissolution of UO_2 and glass waste form		
	Solubility of neptunium-237		
	Formation of radionuclide-bearing colloids		
	Transport within and out of waste package		
Radionuclide concentration reduction during transport from the waste packages	Transport through unsaturated zone	Unsaturated Zone Transport	Unsaturated and Saturated Flow under Isothermal Conditions and Radionuclide Transport
	Transport in saturated zone	Saturated Zone Flow and Transport	
	Dilution from pumping		
	Biosphere transport	Biosphere Transport and Uptake	

As noted in Section 7.2, one of the features of the repository design used in the TSPA-VA was an initial high thermal loading, i.e., 85 MTU/acre, with a drift wall temperature of 200 degrees C. The performance objective for this design concept is to drive the water in the geologic formations around the repository away from the drifts for as long as possible, while radionuclides in the wastes decay and heat emissions from the waste packages decrease. An adverse consequence of the concept is that it produces high temperature levels and temperature gradients, which will accelerate degradation processes and can change the characteristics of the geologic formations. The thermal, chemical, hydrologic, and mechanical factors associated with the high temperatures are coupled in highly complex ways that are difficult to model and characterize with reliable parameter values. The modeling approach used in the TSPA-VA uncoupled these factors, thereby adding to the uncertainty of the TSPA-VA results.

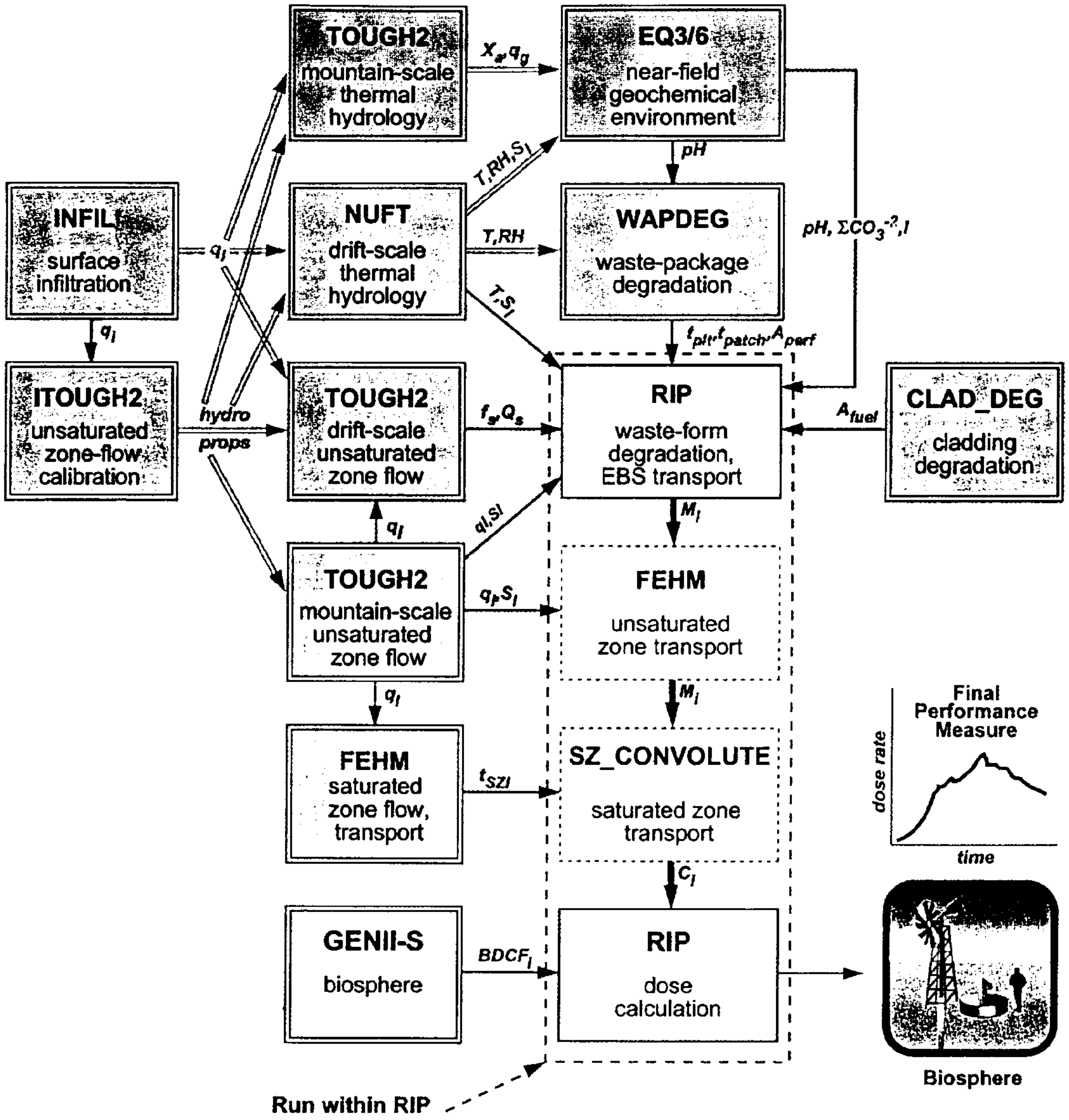
The computer codes and their configuration used in the TSPA-VA are shown in Figure 7-36. As indicated in this diagram, thermal hydrology factors and UZ flow were modeled at both mountain (large) and drift (small) scales. The Repository Integration Program (RIP) code receives input from the codes for the individual performance factors and processes the inputs to calculate radiation doses to the dose receptor(s). Many of the codes shown in Figure 7-36 were developed or adapted specifically for use in the TSPA-VA; details are provided in the VA documentation (DOE98) and supporting documents (DOE98a).

The codes used in the TSPA-VA include considerations of uncertainty and produce characterizations of uncertainty in the assessment results. Four types of uncertainty are considered: parameter value uncertainty, conceptual model uncertainty, numerical model uncertainty, and uncertainty in the occurrence of future events such as earthquakes or human intrusion into the repository. For the TSPA-VA, there was considerable uncertainty in most of the component models and in parameters that represent performance factors that are inherently variable or had a sparse data base. Techniques such as Monte Carlo sampling are used to characterize uncertainty in the results of the assessments; uncertainties in the peak dose rate results of the TSPA-VA evaluations spanned four to five orders of magnitude.

Nine radionuclides were considered in the TSPA-VA evaluations: C-14, I-129, Np-237, Pr-231, Pu-239, Pu-242, Se-79, Tc-99, and U-234. These are the nuclides that prior TSPA work has shown to have the most potential to produce dose effects in the future because of their long half-lives, their high dose consequences (e.g., Np and Pu), or their high mobility in the environment (e.g., Tc-99, and I-129). As discussed below, the highly mobile Tc-99 and I-129 were found to be the source for doses in the 10,000 year time period; Np-237 dominated doses in the period tens-of-thousands to about 300,000 years; and Np-237 and Pu-242 were dominant in the period from 300,000 to one million years.

7.3.2.3 Key Features of the TSPA-VA Base Case Models

This section summarizes key features of the performance factors and computer codes that were used to implement the TSPA-VA. The descriptions are based on information contained in DOE98, Volume 3, Section 4. Highly detailed discussions of the performance factors were provided in the chapters of the Technical Basis Document for the VA (DOE98a), and in topical reports that were discussed as references in the Technical Basis Document chapters.



OUTPUT Parameters

T	Temperature	Q_S	Seep flow rate
RH	Relative humidity	pH	pH
S_l	Liquid saturation	ΣCO_3^{-2}	Carbonate concentration
X_a	Air mass fraction	I	Ionic strength
q_g	Gas flux	t_{pit}	Initial-pit-penetration time
q_l	Liquid flux	t_{patch}	Initial-patch-penetration time
q_i	Infiltration flux	A_{perf}	Perforated container area
M_i	Radionuclide mass flux	A_{fuel}	Exposed fuel area
C_i	Radionuclide concentration	t_{SZi}	Saturated zone transport time
f_S	Fraction of WPs with seeps	$BDCF_i$	Biosphere dose conversion factor
		EBS	Engineered Barrier System

Legend

▣	*External Process Model*
☐	*RIP Cells*
⬚	*Rip Calls External Code*
⇒	*Response Surface Between Process Models*
→	*Response Surface from Process Model to RIP*
➡	*Between RIP Cells and External Code*

Figure 7-36. Computer Code Configuration for the TSPA-VA (DOE98)

Climate

The TSPA-VA assumed there would be three characteristic climate regimes in the future at Yucca Mountain, with periodic recurrence intervals: dry (current conditions), long-term average, and superpluvial. Present conditions were assumed to prevail for the next 5,000 years. Long-term average conditions were assumed to persist for 90,000 years each time they occur, and superpluvial periods were assumed to last for 10,000 years.

Average precipitation rates in the long-term average and superpluvial periods were assumed to be two and three times, respectively, higher than present rates, which average about 170 mm/yr. Two superpluvial periods, in which glaciation is at a maximum and temperatures are a minimum, were assumed to occur in the next million years: one at about 300,000 years and the other at 700,000 years. Between the superpluvials, the 5,000-year dry periods and the 90,000-year long-term average periods alternate. Under these assumptions, about 90% of the next million years experiences the long-term average climate.

The water-table level was assumed to respond to the changes in precipitation, rising by 80 meters from present levels during long-term average climates and 120 meters during the superpluvial periods. One of the modeling consequences of the water-table rise is that the UZ flow path length is shortened.

Unsaturated Zone Flow and Infiltration

On the basis of site characterization data, the repository footprint was divided into six UZ flow and infiltration zones. Three-dimensional steady-state flow models were developed for fracture and matrix flow under current climate conditions and were extrapolated to the wetter climate conditions. Average infiltration rates for the present, long-term average and superpluvial climate conditions were assumed to be 7.7, 42, and 110 mm/yr, respectively. The infiltration rates were therefore assumed to increase by factors of about 6 and 14 from the present rate, even though the precipitation rate increases only by factors of 2 and 3.

Drift Scale Seepage

Characterization of seepage into the drifts was based on modeling of a three-dimensional, heterogeneous fracture continuum surrounding the drifts. The seepage flow rate and fraction of the packages that are affected by seeps were modeled in terms of percolation flux, i.e., the water flux that arrives at the repository horizon after infiltration at the surface and flow through the UZ above the repository. Percolation flux was characterized for each of the six regions of the repository footprint and the three climate conditions, based on site data and the climate model.

The modeling showed that about 10% of the waste packages would be exposed to seeps during the dry-climate period, 30% would be exposed to seeps during the long-term average climate conditions, and 50% would be exposed during the superpluvial periods. The estimates of the fraction of the packages exposed to seeps had a very high uncertainty range in the TSPA-VA evaluations.

Thermal Hydrology

Thermal hydrology addresses the temporal and spatial impact of the spent fuel heat output on the natural system geologic and hydrologic characteristics and on the performance of the engineered features of the repository. Thermal hydrology models are used to calculate temperatures (waste package surface, waste form, drift wall) and relative humidities in the drifts. Values for these parameters provide information needed for other models such as the waste package degradation model and the near-field geochemical environment models. Standard models of heat transfer, and data concerning the physical properties of repository system materials, are used to characterize the thermal parameters.

Near Field Geochemical Environment

The near-field geochemical environment models calculate the time-dependent evolution of the gas and water compositions that interact with the waste package, the waste form, and other materials in the drift. The evolution of changes in gas and water composition is modeled as a sequence of steady-state conditions. The chemical, thermal, hydrologic, and mechanical factors important to the near field environment are in reality coupled, but an integrated model of the coupling and its effects was not developed for the TSPA-VA.

Five separate but interacting models were used in the TSPA-VA to characterize the near field geochemical environment:

- Gas, water, and colloid compositions as they enter the drift
- Composition of the in-drift gas phase

- Chemistry of in-drift interactions of water with the solids and gases in the drift
- In-drift colloid compositions
- In-drift microbial communities

The near-field geochemical environment models are connected to other component models see Figure 7-37). The near-field models receive input from the UZ and thermal hydrology models and from design parameters; they provide outputs to the waste package corrosion model, the waste form model, the UZ radionuclide transport model, and the nuclear criticality model.

Waste Package Degradation

Modeling of waste package degradation was based on waste type contained in the package, whether the packages were dripped on or not dripped on, and their location in the repository. Seepage into the drifts is modeled as a function of the infiltration rate of water and the fracture properties of the rock. With the expected percolation flux, only about one-third of the waste packages are dripped for most of the one million year modeling period. If water seeps onto the surface of a waste package, 100% of the surface is assumed to be wetted. Uncertainty in the corrosion rate of the Alloy 22 corrosion-resistant barrier in the waste package wall was also modeled, and the expected-value base case assumed that a single juvenile waste package failure occurs 1,000 years after disposal. Corrosion of waste package materials was assumed to occur via pits and patches that always encounter seeping water.

Cladding Degradation

Mechanisms included in models for degradation of fuel rod cladding on commercial spent nuclear fuel included some pre-disposal failures, creep failure of zircaloy at high temperatures, total failure of rods clad with stainless steel, fuel rod fracture from falling rocks, and long-term general corrosion failure. Breaching of cladding was assumed to expose all of the waste-form surface in the rod to water that had entered the waste package.

Waste Form Degradation and Mobilization

Dissolution of CSNF was modeled to be a function of pH, temperature, and total dissolved carbonate; model parameters were based on experimental data. Dissolution of vitrified high-level defense waste was modeled as a function of surface temperature and water pH, and a dissolution rate constant for metals was used for degradation of the defense spent fuel from the

N-Reactor. Under the assumption that all spent fuel is exposed and wetted for rods with breached cladding, the spent fuel would be totally dissolved in about 1,000 years. Dissolution of uranium dioxide fuel is known to result in formation of secondary minerals which can trap species such as Np-237 and reduce their release, but credit for this phenomenon was not taken in the TSPA-VA modeling.

Engineered Barrier System Transport

Transport in the EBS was modeled as a series of connected mixing cells, with one cell combining the waste form and waste package, and three pathway cells representing the invert, in orde reduce numerical dispersion in model calculations. The models did not include factors that could defer and decrease radionuclide release after a waste-package wall is breached, such as low seepage rates and partial seepage into the package interior, and in-package dilution. Sorption and diffusional transport was assumed for radionuclide movement through the concrete invert. Consistent with data which indicated rapid transport of plutonium from the Benham weapon test location on the Nevada Test Site, a small fraction of the plutonium mobilized was assumed to be attached to mobile colloids.

Unsaturated Zone Transport

The radionuclide transport model for the unsaturated zone was based on the flow model for that zone. Three flow fields, corresponding to the three climate conditions, and a dual-permeability geologic regime were assumed. Radionuclide movement was modeled using a three-dimensional particle tracking model. Sorption was assumed to occur for Np-237, Pu-239, and Pu-242. Matrix diffusion and dispersion were also assumed to occur.

Saturated Zone Flow and Transport

Flow in the saturated zone was simulated using a coarsely discretized three-dimensional model which establishes the general plume direction and flow path in the geologic media. Radionuclide transport was assumed to occur in six one-dimensional stream tubes corresponding to the six area regions defined for the repository footprint. Based on the recommendations of the saturated zone expert elicitation panel, the specific discharge in all stream tubes was assumed to be 0.6 m/yr, and a dilution factor probability range, with a mean value of 10, was assumed to apply to all of the stream tubes.

Biosphere Transport

Water used by the dose receptor was assumed to be drawn from a well 20 km (12 miles) down gradient from the repository. Dilution was assumed not to occur during pumping, so the radionuclide concentration in the water emerging from the well is the same as the stream tube concentration at the withdrawal location. The dose receptor was assumed to receive doses from all biosphere pathways in accord with site-specific dose conversion factors and the water use and life style habits assumed for the receptor. For the TSPA-VA, DOE assumed the dose receptor is a current-day average adult living in Amargosa Valley. A survey was conducted to obtain lifestyle and dietary data for the dose evaluations.

7.3.3 TSPA-VA Results

DOE produced the following categories of TSPA-VA results:

- Deterministic results for the TSPA-VA base case
- Results of uncertainty analyses using Monte Carlo techniques
- Results of analyses to assess the sensitivity of performance to uncertainties in parameter values
- Assessments of the effect of disruptive events on performance
- Assessment of the effect of design options on performance

Collectively, these assessment results address the expected performance of the repository, the role of the various performance factors in producing the expected performance, factors that could alter expected performance, and the uncertainty in expected performance. The repository performance forecasted for the base case is discussed in Section 7.3.3.1. Uncertainties in the TSPA-VA result are discussed in Section 7.3.3.2.

7.3.3.1 Base Case Expected Repository Performance

The deterministic results for the TSPA-VA base case are responsive to the Congressional mandate for assessment of “...the probable behavior of the repository in the Yucca Mountain geological setting...”. These results were a forecast of the dose rate to the average individual located 20 km from the repository, for time periods up to one million years. Graphs showing forecasts of peak doses throughout the million-year time period were produced, and specific dose-rate values were identified and discussed for time periods of 10,000, 100,000 and one million years.

DOE described the results for the deterministic evaluation in which values for all uncertain parameters were set at their expected values as follows (DOE98, Volume 3, p. 4-21):

> *"1. Within the first 10,000 years, the only radionuclides to reach the biosphere are the nonsorbing radionuclides with high inventories, technetium-99 and iodine-129, and the total peak dose rate is about 0.04 mrem/year.*
>
> *2. Within the first 100,000 years, the weakly sorbing radionuclide neptunium-237 begins to dominate doses in the biosphere at about 50,000 years, with the total dose rate reaching about 5 mrem/year.*
>
> *3. Within the first million years, neptunium continues to be the major contributor to peak dose rate, which reaches a maximum of about 300 mrem/year at about 300,000 years after closure of the repository, just following the first climatic superpluvial period. The radionuclide plutonium- 242 is also important during the one million-year time frame and has two peaks, at about 320,000 and 720,000 years, closely following the two superpluvial periods. There are regularly spaced spikes in all the dose rate curves (more pronounced for nonsorbing radionuclides such as Tc-99 and I-129) corresponding to the assumed climate model for the expected value base-case simulation...these spikes are a result of assumed abrupt changes in water table elevation and seepage through the packages."*

As shown in Figure 7-37, doses to the receptor 20 km from the repository, as a result of the mobile Tc-99 and I-129 radionuclides, first occur about 3,500 years after disposal. These fission products are dominant because of substantial inventory in CSNF, high solubility in seepage water, relatively low decay rate relative to 10,000 years, and neglible sorption on tuff rocks. The scenario presented in Figure 7-38 results from the assumption that a single juvenile waste-package failure occurs at 1,000 years; the "blip" in the curve at about 5,500 years is the result of the change of climate conditions from dry to long-term average at 5,000 years, which causes a major rise in the water table. During the 10,000-year period, 17 additional packages are modeled to fail at various times, beginning at about 4,200 years. These failures contribute to the dose at 10,000 years in accord with the TSPA-VA model assumptions concerning package failure times and conditions.

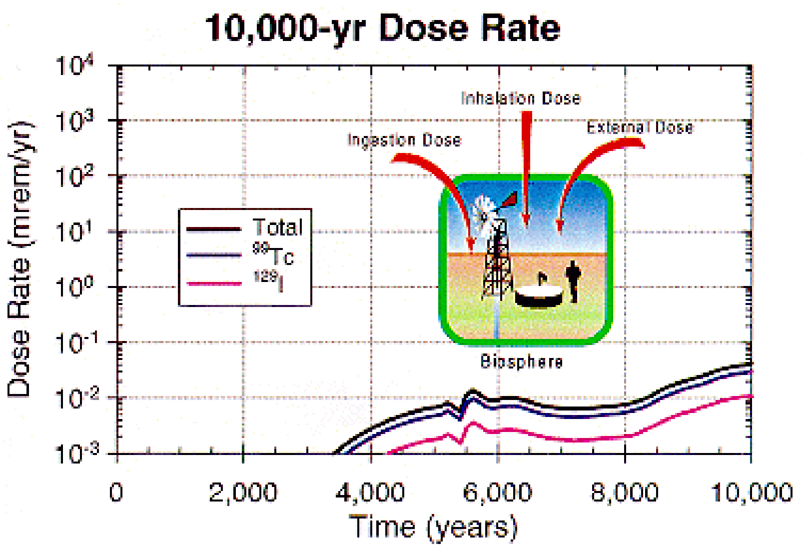


Figure 7-37. TSPA-VA Base Case Dose Rates for Periods Up to 10,000 Years (DOE98)

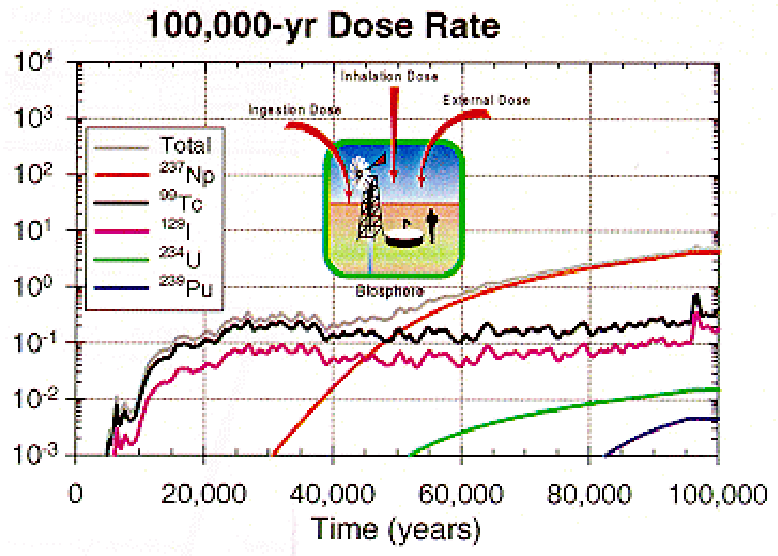


Figure 7-38 TSPA-VA Base Case Dose Rates for Periods Up to 100,000 Years (DOE98)

Dose rate histories for times up to 100,000 years are shown in Figure 7-38. Tc-99 continues to dominate the dose rate up to about 50,000 years, after which the Np-237 dominates the dose rate out to 100,000 years. There is a relatively large inventory of Np-237 in CSNF resulting from the decay of Am-241. The Np-237 does not begin to appear at the dose location until after about 30,000 years, because its release from the waste form is solubility limited and it exhibits some sorption on the rock surfaces along the transport pathway. The Pu-239 does not begin to appear at the dose location until more than 80,000 years have elapsed because it is more strongly sorbed than the Np-237. A small fraction of the Pu-239 is assumed, however, to be attached to colloids that are not sorbed onto the rock surfaces.

As with the 10,000-year results, the dose rate forecasts for periods to 100,000 years are dominated by climate change assumptions and waste package failure history. The jagged appearance of the Tc-99 curve is the result of individual package failures; each small peak corresponds to a failure. This illustrates one of the key features of the TSPA-VA modeling scheme: because features such as slow drip entry to the package interiors and in-package dilution, which provide storage capacity along the transport path, were not included in the models, the nonsorbing species such as Tc-99 directly track release behavior, and concentrations are simply attenuated by dilution along the pathway. The sorbing and solubility-limited species, such as Np-237 and Pu-239, have the capacity for storage along the transport path because of these properties, but the effects would have been more exaggerated if factors such as in-package dilution had been included in the TSPA models.

As shown in Figure 7-39, Np-237 continues to dominate the dose rate from 100,000 years all the way to the end of the million-year dose evaluation period. At about 300,000 years, Pu-242 becomes the second most important contributor to dose and remains in this role, at a level about a factor of ten less than that of the Np-237, to the end of the dose evaluation period. The contribution of other radionuclides to dose during the long-range time frame is insignificant.

The dose rate after about 300,000 years is seen in Figure 7-39 to be essentially constant. This is because, in the TSPA-VA modeling scheme, the repository as a source term for radionuclides released to the environment goes into essentially steady state. All of the packages that are modeled to fail have failed, the seepage fluxes into the repository and into the packages have become virtually the same and constant, and the rate of change in exposure of waste form has become constant.

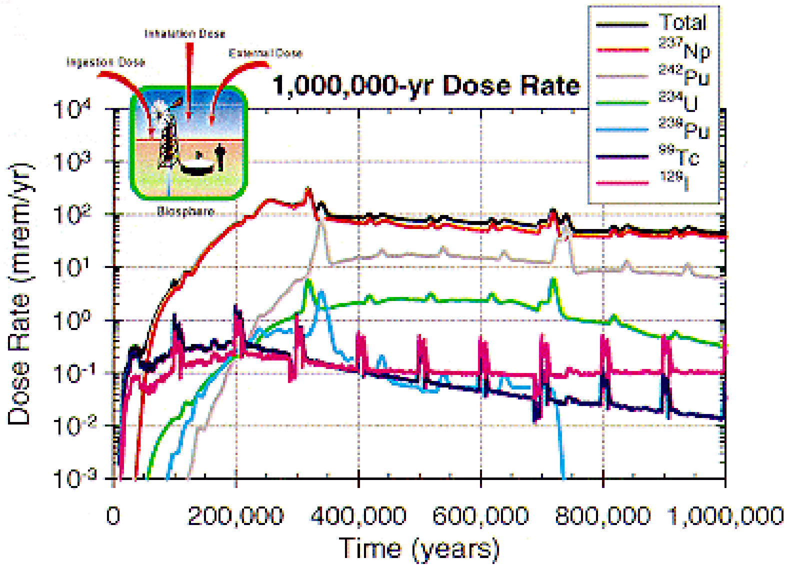


Figure 7-39. TSPA-VA Base Case Dose Rates for Periods Up to One Million Years (DOE98)

The dominant effect of waste package failure history and climate conditions on dose rates continues to the end of the million-year dose evaluation period. At about 200,000 years, cladding degradation begins to contribute to the exposed waste form area, and at times greater than about 700,000 years, waste packages that are never dripped on, which total about 55% of the package inventory, begin to fail as a result of low corrosion rates in a non-wetted condition over a very long time frame.

The base case TSPA results for the VA repository show that the performance of the highly complex and multi-element system is strongly dominated by very few factors. In brief:

- Performance is dominated by assumptions concerning waste package failure history and climate, and the effect of these factors on predicted doses is primarily a consequence of the assumptions concerning juvenile package failures and climate change.

- Three nuclides dominate the forecast doses: Tc-99 and I-129 in the shorter time frames and Np-237 in the longer time frames. The dose levels associated with the Np-237 are higher than those associated with the technetium and the iodine, in large measure because the health consequences of a unit quantity of Np-237 are much greater than those for the technetium and iodine.

- The fact that the dose results clearly reflect the occurrence of climate changes and individual package failures shows that the TSPA-VA modeling system is fundamentally simple. Factors in performance that would serve to smooth and smear the consequences of phenomena that change system conditions were omitted from the models.

7.3.3.2 Uncertainty in the TSPA-VA Results

The Monte Carlo type of analyses that were done to assess the uncertainty in the TSPA-VA deterministic base-case results showed an uncertainty range spanning about four to five orders of magnitude throughout the million-year period, as shown in Figure 7-40. These results were obtained by using statistical methods to select values from the distributions for the uncertain parameters used in the TSPA-VA models. For each of the three time frames (i.e., 10,000, 100,000, and one million years) one hundred such runs were done, and a few 1,000-run studies were done to demonstrate that the uncertainty ranges found for the 100-run studies were representative.

The large uncertainty range, i.e., spanning four to five orders of magnitude, is in part due to the many uncertain parameters in the TSPA-VA computer codes. The RIP code alone, for example, contains 177 uncertain parameters, and there are many more in the codes that have inputs to RIP. Another possible cause of the wide uncertainty range is that many of the uncertain parameters themselves have wide uncertainty ranges, either as a result of use of a broad range of possible values because the actual value of the parameter is poorly known, or because the parameter is inherently highly variable. It would be difficult, if not impossible, to sort out the sources and principal causes of the uncertainty range. The uncertainty range for the TSPA-VA results is therefore a consequence of the specific way uncertainty was used in assigning numerical value distributions to parameters in the TSPA-VA models and codes.

Another source of uncertainty, not reflected in the results of the TSPA-VA studies, is the possibility that some of the models used in the codes may not be correct, e.g., because of a sparse data base, or, as in the case of modeling of the near-field geochemical environment, because coupled phenomena were uncoupled to simplify modeling. This type of uncertainty should be regarded as uncertainty in the conceptual models for the waste containment and isolation systems. In translating conceptual models into calculational models, conservative assumptions are typically made about processes which should be included and how the processes would operate. This is done, in part, for modeling convenience, and, in part, because the level of

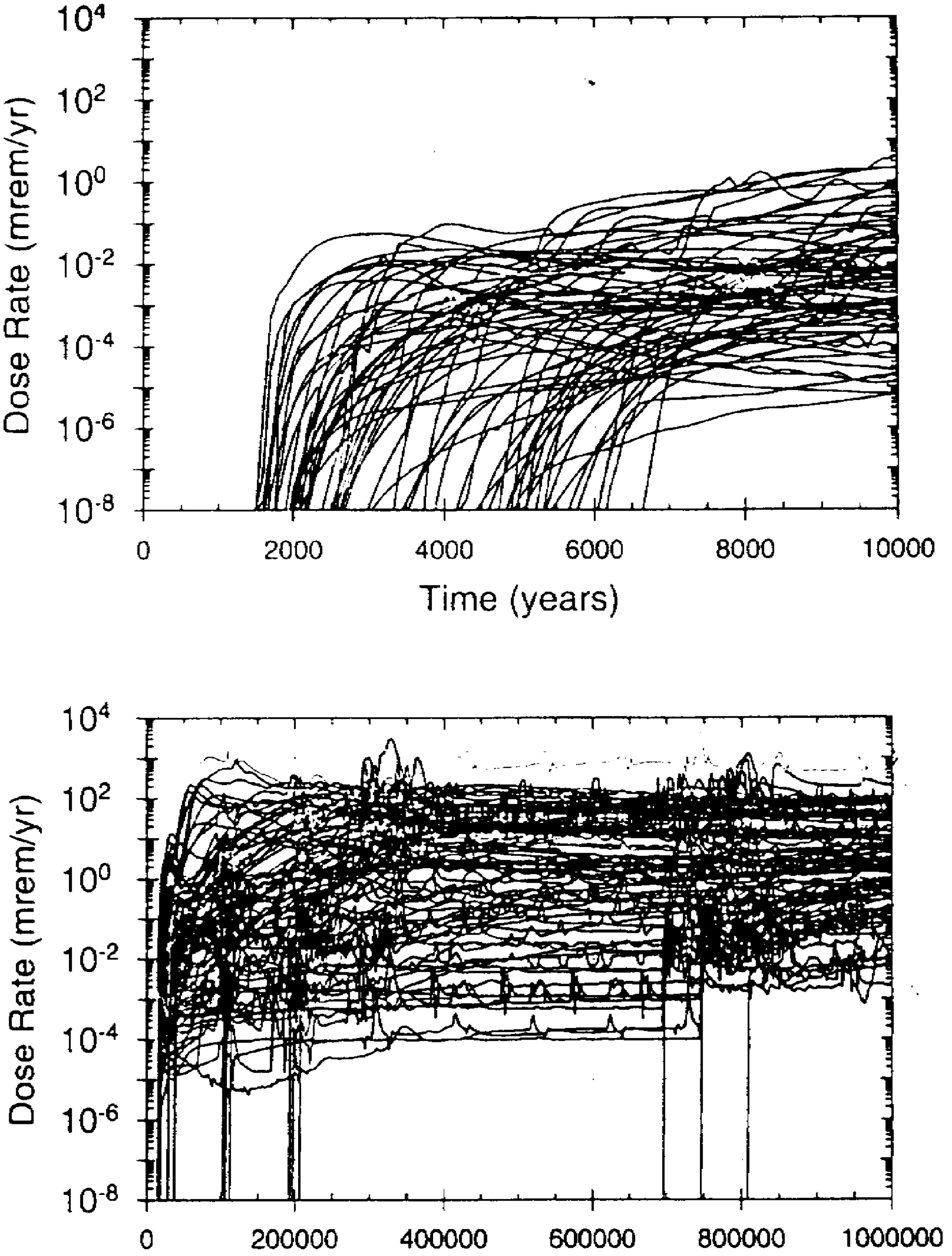


Figure 7-40. Uncertainties in the TSPA-VA Base Case Results (DOE98)

process complexity cannot be handled manageably. These assumptions can have significant implications for interpreting the results of performance assessments, and should be understood when interpreting the results. (See Section 7.3.3.5 for additional discussion of conservatism in the TSPA-VA modeling.)

In evaluating the status of knowledge and uncertainty as a prelude to selecting further work to improve the TSPA methodology for a License Application (DOE98, Volume 4), DOE often noted that the models used in the TSPA-VA might not adequately capture the full range of possibilities. If this is indeed the case, and the uncertainty in parameters or models has to be expanded in order to embrace the full range of possibilities (as opposed to simply revising the model in response to better information), the uncertainty ranges for future TSPA results might actually be broader.

DOE used a technique known as Stepwise Regression Analysis to determine which of the performance factors were most important to the uncertainty results. These evaluations showed, for the 10,000-year time period, that the fraction of the packages contacted by seepage, the mean Alloy 22 corrosion rate, the number of juvenile failures, and the saturated zone dilution factor are the most important performance parameters. For the 100,000-year period, the most important parameters were the seepage fraction, the mean Alloy 22 corrosion rate, and the variability in the Alloy 22 corrosion rate. For one million years. the most important factors were found to be the seepage fraction, the saturated zone dilution factor, the mean Alloy 22 corrosion rate, and the biosphere dose conversion factors. The fraction of waste packages contacted by seepage water was the dominant performance factor for all three time periods. It is the dominant factor for TSPA modeling of repository system performance because it has a direct effect on the number of waste packages that fail, and it has a very large uncertainty.

Additional sensitivity studies were done to determine the performance factors of secondary importance to the TSPA-VA results. In these analyses, the performance factor of primary importance were held constant, and Monte Carlo runs were done for the other uncertain parameters. The performance factors that were held constant at their baseline values were the infiltration rate and mountain-scale saturated zone flow rates, the fraction of the waste packages contacted by seepage, the seepage flow rate, the Alloy 22 mean corrosion rate, and the Alloy 22 corrosion rate variability.

With the above parameters held constant, the parameters of principal secondary importance at 10,000 years were found to be the saturated zone dilution factor, the biosphere dose conversion factors, the solubility of technetium, and the fraction of seepage contacting a package that enters a failed package. The factors that were important for 10,000 years were found to be also important for 100,000 years, except that the solubility of neptunium replaced the solubility of technetium as an important factor, and the fraction of saturated zone flow in alluvium was added to the list. At one million years, the most important factors were the saturated zone dilution factor, the cladding failures by corrosion and by mechanical disruption, the biosphere dose conversion factors, the saturated zone longitudinal dispersivity, and the saturated zone alluvium fraction. In all time frames, the most important of these secondary factors was the saturated zone dilution factor.

All of these sensitivity findings reflect the fundamentals of repository system performance: the potential doses depend primarily on the fraction of waste packages intercepted by seepage, the amount of waste form available to be a source of radionuclides, the amount of water available to pick up the radionuclides and to transport them to the environment, the amount of water available to dilute radionuclide concentrations, and the extent and means of interaction of the dose receptor with the contaminated water.

7.3.3.3 Effects of Disruptive Events on Performance.

The TSPA-VA evaluated the effects of four types of disruptive events on repository performance: basaltic igneous activity, seismic activity, nuclear criticality, and inadvertent human intrusion. The basis for inclusion of evaluations of the effects of disruptive events on repository performance includes the probability of occurrence of the event, the consequences of occurrence, and any regulatory requirements that mandate or exclude consideration of disturbances.

The igneous activity evaluations considered events in which molten igneous material is cooled within the earth or on the surface. In the case where magma reaches the surface, explosive releases may carry radioactive materials directly into the atmosphere. Cooling of magma within the earth may involve destruction of waste packages so that radionuclides in the waste form are more accessible for release and transport.

Results of the direct-release igneous activity evaluations showed that the maximum dose rate from this volcanism would be about two million times less than for the base case ground water contamination scenario. The underground-cooling scenarios showed that dose rate peaks would occur tens of thousands of years after the actual magma intrusion event.

The seismic activity studies considered phenomena such as rockfall onto waste packages as a result of earthquakes, and the effects of seismicity on the hydrologic regime in the near field and in the saturated zone. These studies showed that rockfalls could not contribute significantly to waste package degradation until after at least 100,000 years and that changes to the hydrologic regimes would be negligible. Overall results of the analyses showed that seismic events would have almost no effect on repository performance over one million years.

The potential for nuclear criticality within waste packages and external to the packages after transport of fissionable material from the package was investigated within the TSPA-VA. The evaluations were done assuming that criticality occurs 15,000 years after emplacement, which is when the commercial spent fuel is most reactive. The analyses determined that criticalities external to the waste packages are not a credible event, and that criticality within a package is extremely unlikely and would have insignificant consequences. Criticality within a waste package is extremely unlikely because only 8% of the commercial fuel waste packages contain sufficient fissile material to acheive a critical mass and only 10% of the waste packages are expected to be breached in 40,000 years. Breached waste packages must retain sufficient water to act as a moderator for the nuclear chain reaction to be sustained and DOE has estimated that only 25% of the breached waste packages will hold water for a period sufficient to flush out boron which is included in the waste package as a neutron absorber. Even if criticality did occur within the waste package, the incremental radioactivity is less than the normal radioactivity from most waste.

In keeping with the recommendations of the NAS panel that developed the technical basis for the Yucca Mountain standards, a stylized human intrusion scenario was characterized and evaluated. Intrusion of a waste package by an 8-inch drill bit, as a result of search for water, was assumed. The bit was assumed to penetrate the package and the mountain stratigraphy to the water table, with large quantities of pulverized fuel being transported to the bottom of the bore hole, which was never sealed. Water would then dissolve the fuel inventory at the bottom of the bore hole and transport radioactive material to the dose receptor location. The intrusion was assumed to occur at 10,000 years, which is the first time at which it is estimated the drill bit could penetrate the package wall. The NAS panel did not feel it would be useful to assess hazards to drillers or to the public from radioactive materials transported directly to the surface since these risks would be the same for all geologic repositories.

The total amount of fuel deposited at the bottom of the bore hole was assumed to range between 550 and 2,700 kilograms (1,200 and 6,000 pounds), which corresponds to about 5 to 22% of the total spent fuel inventory in the package. The actual mass of fuel that would be intercepted by the 8-inch drill would be about 160 kg, so the analyses assumed that large quantities of fuel would be entrained by the bit as it passed through the package.

The analyses for this intrusion scenario showed that the consequent radionuclide releases for the 2,700 kg release would produce a blip in the dose rate curve, in comparison with the base case, that starts at about 11,000 years, peaks at 12,000 years, at levels about 145 times higher than the base case dose rate at that time (i.e., 1 mrem/yr), and returns to base case levels at about 14,000 years. The 550-kg spent fuel release from intrusion produces a dose rate at 12,000 years that is 3.7 times the base case dose rate. All effects of the intrusion on dose rate are gone by 150,000 years. The TSPA-VA observed that the effects of the intrusion on dose rates are significant only for times near the occurrence of the intrusion, and that the maximum resulting dose is 1 mrem/yr.

7.3.3.4   Effects of Design Options on Performance

The TSPA-VA included evaluation of the effect , on repository performance, of design features that were not included in the VA reference design. The three features considered were emplaced drift backfill, drip shields, and ceramic coating of the disposal containers, with backfill. The objective for use of these design options would be to reduce and defer liquid water contact with the waste package.

7.3.3.4.1 Effects of Backfill

The backfill was assumed to be crushed tuff, emplaced 100 years after the end of emplacement operations. The backfill will initially perform as a thermal blanket for the waste packages, and cause a temperature spike of as much as 80-90°C. The temperature spike might cause a slight increase in the waste package corrosion rate, but it would also delay the rate of increase of relative humidity as the heat emissions from the waste packages decrease and the repository system cools. A potentially major effect of backfill would be to change the potential for, and patterns of, seepage water contacting the waste packages. This effect was not modeled in the TSPA-VA analyses.

The analyses for the assumed backfill effects showed that the use of backfill would defer corrosion of the Corrosion Allowance Material, but corrosion of the Corrosion Resistant Material would be virtually unaffected based on the modeling assumption that corrosion of this material is driven by whether or not dripping occurs and the same dripping conditions are assumed for the case of backfill and no backfill . Use of backfill would therefore have little effect on repository performance if the backfill does not reduce or defer contact of seepage water with the waste packages. The backfill might actually have effects such as diverting the seepage water around the waste packages or reducing the amount of seepage that gets to the package as a result of evaporation, but a basis for modeling such effects was not available for the TSPA-VA.

7.3.3.4.2 Effects of Drip Shields

The drip shields were assumed to be made of Alloy 22 and to be 2 cm (0.8 in.) thick. The shields would be shaped like a Quonset hut, shrouding the waste packages but not touching them. The dripshields would be covered with backfill, emplaced 100 years after emplacement of the waste packages was completed. The shields upper surfaces were assumed to be totally wet in dripping regions of the repository, and they were assumed to fail only by general corrosion. After drip shield failure, 10% of the waste package area under the failed shield was assumed to be wetted (in contrast, the base case analyses assumed 100% of the package surface area would be wetted) because only a small fraction of the drip shield surface area was modeled to fail.

TSPA-VA results based on the above assumptions showed that the drip shields enhanced the overall waste package lifetime by more than 100,000 years. Dose rates for the first 300,000 years are reduced by one to two orders of magnitude in comparison with base case results. After 500,000 years, the drip shield dose projections become the same as those for the base case. The results were interpreted to indicate that the life span if the drip shield is the key determinant of improved performance.

As a result of these findings, drip shields are included as a design feature for the repository design expected to be selected as the reference design for the Site Recommendation and the License Application (see Section 7.2.2.5).

7.3.3.4.3 Use of Ceramic Coating of Disposal Containers with Backfill

This design option involves coating the waste packages with a ceramic material in order to delay corrosion of the outer wall of the packages (in the VA design, A 516 carbon steel). Backfill is added to the repository to protect the ceramic coatings.

Performance of this design concept was modeled assuming that the ceramic coating functions as a barrier to oxygen transport to the carbon steel package wall. For the assumed conditions, the analyses determined that the ceramic coatings would not be breached for more than 300,000 years. Dose rates would not begin until about 500,000 years, and at one million years the dose rates would be nearly two orders of magnitude less than those for the TSPA-VA base case.

If ceramic coatings perform as modeled for the TSPA-VA, they would have a profound effect on repository system performance. At this time, however, there are uncertainties and concerns associated with potential for defects and flaws in the coatings, differential thermal expansion between the coating and the substrate that could result in cracks in the coating, and dissolution of the coating over long time periods. Analysis of these effects is needed before the potential benefits of use of ceramic coatings can be verified.

7.3.3.5 Conservatism In The TSPA-VA Base Case Results

The TSPA-VA base-case results (an expected (average) value dose rate of 0.04 mrem/yr 10,000 years after disposal, to a reference person 20 km downstream) are a consequence of choices that were made concerning performance parameter values, performance models, and assumptions. This section discusses conservatism that was exercised in making the TSPA-VA choices, and the effects of conservatism on the base case results. Similar discussions are provided for the NRC performance assessments (Section 7.3.5.3) and the EPRI assessments (Section 7.3.6.4).

Performance Parameters

The TSPA-VA base-case evaluations used expected values of performance parameters, based on available information. Expected values for some of the parameters, such as the dilution factor for the saturated zone and corrosion rates of Alloy 22, were based primarily on results of expert elicitations because of limited availability of data at the time that the TSPA-VA analyses were performed. The parameter values developed by the expert elicitations may be conservative because the experts are, themselves, working with limited information. Expected values of parameters, and the uncertainty ranges for parameters that are inherently variable, may change in the future as a result of data additions, but the TSPA-VA analyses sought to be as realistic as possible, rather than conservative, in their choices of performance parameter values.

Performance Models

Conservatism in the suite of performance models and computer codes used for the TSPA-VA analyses was introduced by using simplified models and by omitting from the suite of models some performance factors that could have significant impact on predicted doses. Examples of this type of conservatism include:

- Dilution and transport delay for radionuclides released from the waste form but in water still within the failed package were not considered. Under realistic package failure conditions during the first 10,000 years, when disruptive failure scenarios are insignificant, water will fill the package interior very slowly from a penetration in the top. By the time that radionuclide release and in-package transport occurs, temperature gradients will be too low to drive advective transport processes, and temperature levels will be too low for inside-to-outside corrosion of the Alloy 22 to occur and create an exit at the bottom of the package. Radionuclide transport rates within the package will therefore be low, the package interior will have to fill with water in order to enable radionuclides to exit through the same penetration that provides water ingress, and the volume of water to fill the package interior will be available to provide dilution. Radionuclide releases to the exit of the package may therefore be greatly delayed, and concentrations at the package exit would be much lower than for the no-dilution assumption.

- Release of radionuclides from a breached waste package was assumed in the VA models to begin immediately after the waste package was breached, i.e., an exit hole in the metal container was assumed to be created as soon as the container wall was breached by corrosion. In reality there would be a time delay before an exit hole at another location on the container was developed. This time delay could be relatively short if exterior corrosion was taking place concurrently at opposite sides of the container, or it could be very long if, as indicated above, the exit pathway had to develop from inside the container. By delaying the exit of radionuclides the actual containment time of the waste containers would be significantly increased and doses during the regulatory time frame would be consequently decreased.

- Dilution of radionuclide concentrations during transit of the unsaturated zone from the repository to the water table was not considered. When few packages are failed and releasing radionuclides (in the TSPA-VA, only 18 of 10,000 packages are failed at 10,000 years), uncontaminated percolation water adjacent to contaminated streams emanating from the failed waste packages could provide extensive dilution as a result of mixing of contaminated and uncontaminated water in the fracture and matrix flow paths. This mixing would lower the radionuclide concentrations at the start of saturated zone transport and result in lower predicted doses to the receptor.

- A simple, one-dimensional model of radionuclide transport along the saturated zone flow paths from the repository to the dose receptor location was used, and dilution of initial SZ radionuclide concentrations under the repository was assumed to occur at the end of the path, in accord with dilution factors recommended by experts (for the base case, a dilution factor of 10 was used). Processes that could delay and disperse radionuclide transport along the pathway, and therefore would reduce the predicted dose rates to the receptor, were not included in the modeling.

- Dilution during well pumping by the dose receptor was assumed not to occur. This expected dilution process, which is included in NRC modeling of repository performance, would reduce predicted doses to the receptor.

These processes and phenomena were omitted from TSPA-VA modeling of repository performance because at the time the data base for characterizing the relevant performance parameters and their uncertainties was limited or non-existent. Also, the magnitude of these effects is difficult to quantify with high confidence even with site characterization and laboratory work focused on them. However, these processes would be expected to function in the actual repository environment, and reasonable but cautious estimates could be made to support assessments, through a combination of data collection and expert judgment.

Rather than choosing to incorporate models for these processes in the TSPA-VA assessments, with estimated values of the parameters used in the calculations, they were omitted from the suite of TSPA-VA models. This approach had the consequence of producing a spectrum of performance results that are an assessment of a potentially very conservative performance scenario, incorporating some unrealistic modeling assumptions. Omission of these modeling features introduces a significant level of conservatism in the assessment results whereas better performance would reasonably be expected.

Additional data (e.g., additional characterization of the SZ geology and hydrology), may enable inclusion of at least some of these performance factors in the TSPA for the LA. Their omission introduces conservatism to the TSPA results, but also avoids licensing issues that may be difficult to resolve unless a data base adequate to support their use is available.

Conservative Assumptions

The TSPA-VA evaluations included conservative assumptions for some of the key performance factors, as follows:

- In the base case, early failure of a waste package was assumed to occur at 1,000 years as a result of an imperfection such as a poor weld. Performance parameters selected in association with this assumption (e.g., the size of the hole on the package wall) were such that nuclide releases from this single package were a dominant factor in the predicted base case dose rate at 10,000 years.

- The Corrosion Resistant Material for the waste package wall, Alloy 22, was assumed to be penetrated rapidly by crevice corrosion as a result of being under carbon steel in the VA waste package design. This assumption was derived from the waste package expert elicitation, which conservatively interpreted the highly limited data base for the corrosion performance of Alloy 22.

- In characterizing corrosion processes, the TSPA-VA assumed that all ground water seeping into the emplacement drifts contacts the waste packages, even though the package width is only one-third the width of the drift, thereby overstating the amount of water available to cause corrosion. In addition, the entire surface of a waste package wetted by seepage water dripping onto the package was assumed to be wetted, and all seepage water contacting the package was assumed to enter the package wall penetration(s) when they occur. The TSPA-VA support analyses (DOE98a) recognized that only a small fraction of the waste package surface would be wetted (the total amount of water contacting the package each year is estimated to be on the order of 20 liters), and that only a fraction of the seepage water contacting the package would enter the wall penetration (e.g., because corrosion products would block entry). Because of uncertainties in placing values on the relevant performance parameters, these factors, which could greatly defer and diminish radionuclide release from the waste form, were omitted from the TSPA-VA evaluations and the bounding conservative assumptions were used.

- The TSPA-VA assumed that 0.1% of the Zircaloy-clad commercial spent fuel rods emplaced in the repository will be “failed” at the time of emplacement, that the spent fuel contents of each penetrated waste package will include 1.15% stainless-steel-clad fuel rods, all of which fail completely and immediately when the package wall is penetrated, and that all waste form area in failed fuel rods is exposed and contacted by water that enters the package. Overall, therefore, 1.25% of the waste form area in a failed package was assumed to be exposed and wetted. In the context of the TSPA-VA evaluations this was considered by some (i.e., NRC staff and the NWTRB) to constitute cladding “credit” because only a small fraction of the waste form in a failed package was assumed to be exposed and wetted. The TSPA-VA assumptions may in fact greatly overstate the extent of exposed waste form area. An extensive data base shows that “failures” of spent fuel cladding are predominantly hairline cracks which would expose only a small waste form area. In addition, the Zircaloy cladding is not susceptible to significant degradation after disposal, and there are only about 2,100 stainless-steel-clad subassemblies, which could be packaged together in less than 100 of the 10,000 waste packages. These segregated packages could be made more failure resistant by using some of the design options assessed in the VA, such as drip shields. With a greatly prolonged waste package lifetime the level of assumed cladding “failure” at emplacement would be lowered by an order of magnitude with consequent lowering of the dose to the receptor. In summary, if only the penetrations of Zircaloy cladding that exist at emplacement allow water to contact the waste form, and if extreme assumptions concerning stainless-steel-clad spent fuel are avoided, the DOE assumptions could overstate the waste form area available for radionuclide release by as much as three orders of magnitude.

7.3.4 Reviews of the TSPA-VA

Formal reviews of the DOE Viability Assessment and the TSPA-VA were documented by the Nuclear Regulatory Commission, the TSPA-VA Peer Review Panel, and the Nuclear Waste Technical Review Board. Their comments are summarized below.

7.3.4.1 NRC Review of the TSPA-VA

In a March 1999 letter to the NRC Commissioners, the NRC Staff provided comments on the TSPA-VA (NRC99c). In addition, the NRC provided some informal feedback to DOE during the May 25-27, 1999 DOE/NRC Technical Exchange (NRC99b). The NRC's feedback was based primarily on a comparison of the TSPA-VA with NRC's TPA 3.2 performance assessment. Details of TPA 3.2 are presented in Section 7.3.5. As discussed in that section, there are substantive differences in the models and parameters used by the two agencies. The purpose of this section is not describe the differences between the TSPA-VA and TPA 3.2 but rather to summarize some of the key NRC comments on the TSPA-VA.

The NRC Staff review covered: (1) the preliminary design concept for the critical elements of the repository and the waste packages; (2) the TSPA based on this design concept and data available as of June 1998; and (3) the license application (LA) plan. The Staff did not review the DOE cost estimates to construct and operate the Yucca Mountain repository. The review focused on those issues that needed to be addressed before the LA is issued (scheduled for 2002) to insure that the application will be complete and minimize the need for a protracted license review. The NRC agreed with DOE's position that work should proceed toward a decision on recommending the Yucca Mountain site as a repository for high-level waste.

There were a number of areas where the NRC Staff did not have major comments at the time of its review based on general agreement with DOE on the particular issues. These included: mechanical disruption of the waste packages; radionuclide release rates and solubility limits; spatial and temporal distribution of flow in the unsaturated zone (UZ); distribution of mass flux between fractures and matrix in the unsaturated zone; retardation in the UZ fractures; retardation in the water-production zones and alluvium; dilution of radionuclides in the ground water from well pumping; airborne transport of radionuclides; dilution of radionuclides in the soil; and location and lifestyle of the critical group. This is not to say that these processes are insignificant; rather, there were no significant issues in these areas at the time of the reviews.

Areas where the Staff had significant comments included:

- Repository design
- Waste package corrosion
- Quantity and chemistry of water contacting waste packages and waste forms
- Saturated zone flow and transport
- Volcanic disruption of the waste packages
- Quality assurance

With regard to repository design, NRC expressed concern as to whether adequate time was available before the LA is scheduled for submittal to address all the design options under consideration, select a reference design, develop data and models, and conduct the analyses required to produce an LA which is complete and of high quality.

Doses received by down gradient receptors are highly sensitive to the corrosion performance of the waste packages. The DOE is exploring several alternatives to the waste package design proposed in the TSPA-VA, which was a 10-cm outer layer of carbon steel corrosion allowance material and a 2-cm inner layer of Alloy 22 corrosion resistant material. It was not clear to the

NRC that the DOE would be able to gather adequate long-term corrosion data in time to definitively support the LA. The TSPA-VA relied heavily on expert elicitation rather than long-term test data and this is a significant weakness.

The amount and chemistry of the water which contacts the waste packages is of critical importance not only to waste package lifetime but also to release of radionuclides once the waste package is breached. The NRC concluded that “the range of activities outlined in the LA Plan are unlikely to provide an adequate licensing basis for assessing the quantity and chemistry of water contacting waste packages and waste forms. .... Additional data and analysis of seepage under both isothermal and thermal conditions will be required for a complete LA.”

The NRC was not satisfied that flow and transport in the saturated zone from beneath the repository to a receptor 20 km down gradient had been adequately characterized. Additionally, the NRC did not concur with the DOE’s view that saturated zone uncertainties were a “moderate” contributor to receptor dose uncertainties. This descriptor was inappropriately optimistic based on sensitivity studies conducted by both organizations. The Staff expressed concerns that the location where ground water enters the alluvium (which delays radionuclide migration) was not well documented. High permeability features between the repository and the receptor could alter the flow direction away from the alluvium and confine the flow to the fractured tuffs.

Based on Staff review, the NRC concluded that the consequences of volcanism were understated in the TSPA-VA. The DOE assumptions on physical conditions were not representative of basaltic volcanism at Yucca Mountain. In addition, the DOE’s models did not consider the impact of the dynamic forces produced by the volcanism on waste packages in a volcanic conduit.

Implementation of an appropriate Quality Assurance (QA) program has been an on-going problem. The NRC has reviewed and accepted the DOE’s QA program on procedural basis. However, audits and surveillances have identified deficiencies in implementing the program. Some data in the technical data bases are not traceable. The NRC is concerned that the LA Plan did not recognize these implementation deficiencies and provide for remedies.

The NRC staff provided some additional reactions to the TSPA-VA in the May 1999 Technical Exchange (NRC99b). The TSPA-VA documentation included several features which facilitated the NRC's understanding of the DOE performance assessment. These included extensive use of plots of intermediate outputs such as time-dependent Tc-99 release from a waste package. Plots of the performance of sub-systems such as the number of waste packages which failed as a function of time were also valuable as were dose rate plots which showed the mean, median, 5th, and 95th percentiles over time. The DOE's presentation of the results of sensitivity analyses and the dose rates expected with alternative conceptual models also enhanced the NRC's understanding of the TSPA-VA. On the other hand, the NRC felt that there were areas where transparency and traceability could be improved. The NRC staff noted that the flow of key information between the RIP computer code and external process models was difficult to trace. The NRC also concluded that there was inadequate sampling of parameters potentially important to repository performance and they could not determine whether correlations between sampled parameter had been properly addressed. The Staff suggested that a table listing all important parameters and their assigned distributions would significantly facilitate review.

The NRC felt that both agencies needed to have a better technical basis for establishing the initial waste package failure levels. Improved linkage was required between initial defects and waste package failure rates. This would involve consideration of the detectability of initial defects and consideration of the expected performance of the defective waste packages. Further, with regard to long-lived waste packages, the NRC averred that there were potential failure processes such as stress corrosion, microbial activity and exposure to alternating wet/dry cycles which could accelerate failure. These processes were not considered by either organization.

The NRC concluded that there were no major performance-affecting differences in the approaches taken by the two organizations with regard to ground-water infiltration and deep percolation. However, the modeling approaches taken for unsaturated zone flow and transport differed markedly.

In near-field modeling the DOE did not consider that penetration of the boiling isotherm in the drift wall could occur by water flowing down a fracture. The NRC concluded that the DOE's assumption that water will not contact a waste package until the waste temperature drops below the boiling point was not conservative.

The NRC observed that the TSPA-VA methods for calculating biosphere dose conversion factors (DCF) were consistent with the NRC approach, but the Commission raised some questions as to whether the procedures used for sampling the DCF distributions created modeling inconsistencies. The NRC also felt that the documentation on dose parameters used in the TSPA-VA needed to be improved.

The NRC concluded that the model for igneous activity used in the TSPA-VA was inadequate. Additional work would be required to develop acceptable models. However, based on discussions between the DOE and the NRC subsequent to publication of the TSPA-VA, the NRC was of the opinion that acceptable modeling approaches can be developed before the License Application is submitted.

7.3.4.2 Review by the TSPA Peer Review Panel

DOE created the TSPA-VA Peer Review Panel to provide the Civilian Radioactive Waste System Management and Operating Contractor with a formal, independent review and critique of the TSPA-VA (PRP99). In its review of the Viability Assessment, the Panel was charged with considering both the analytical approach used and its traceability and transparency in assessing the probable behavior of the repository. Factors evaluated in assessing the analytical approach included:

- Physical events and processes included in the assessment
- Use of appropriate and relevant data
- Assumptions made
- Abstraction of process models used in total system models
- Application of accepted analytical methods
- Treatment of uncertainties

The Panel concluded that, due to the complexity of the system and the nature of the current or reasonably obtainable data, it may be impossible for any technical team to develop the analytical capabilities to prepare a credible assessment of the probable future behavior of the repository. The long time scales which must be considered, coupled with the complexity of the geologic setting, compound the analytical problems. The Panel suggested that dealing with these complex coupled processes can best be handled through bounding analyses or by incorporation of engineered features which minimize the effects of these processes.

In the Panel's words, a credible assessment "*would have needed to include:*

- *Component subsystem models that capture important and relevant phenomena;*
- *Adequate databases;*

- *Proper coupling between the subsystem models; and*
- *Tests of modeled behavior".*

Although the TSPA-VA offers many examples of partial, even substantial, success in each of these four areas, the Panel has also observed examples of important deficiencies in each.

- Concerning subsystem models, the final dose estimates within the TSPA-VA rest in large part on potentially optimistic, or at least undemonstrated, assumptions about the behavior of certain barriers in the system (for example, performance of the cladding and the waste package).

- Concerning databases, some of the important analyses are not supported by an adequate database, (for example, databases for corrosion of spent fuel alteration products and the saturated zone analysis).

- Concerning coupled processes (that is, thermohydrological, thermomechanical, and thermochemical effects) and the data and models that support them, the Panel believes that it may be beyond the capabilities of current analytical methodologies to analyze systems of such scale and complexity. For this reason, the effects of coupled processes can probably best be dealt with through a combination of bounding analyses and engineered features designed to minimize the effects of such processes.

- Concerning tests of modeled behavior, the TSPA-VA does not contain the convincing direct measurements or confirmation of the modeled behavior of components or subsystems for which testing is feasible. This testing should be part of the analyses of such a complicated system."

The Panel concluded that the sensitivity analyses in the TSPA-VA did not provide sufficient insights to overcome these deficiencies and uncertainties.

The Panel expressed concern over the lack of data relating to the performance of the waste packages and reliance on instead on expert elicitation. The Panel stated that DOE must define the environmental extremes to which the Alloy C-22 corrosion resistant liner will be exposed and establish experimentally the critical temperature for crevice corrosion in these aggressive environments. The need to obtain more and better data to enhance performance assessment credibility was a repeated theme throughout the Panel's report.

The behavior of the waste packages is strongly dependent on the extent to which contact with infiltration water seeping into the drifts is minimized. The Panel was not convinced that the

TSPA-VA base case correctly captured seepage into the drifts over long periods of time. The Panel concluded that “Better characterization of the hydrologic properties near the drifts, improved modeling, consideration of coupled effects, and additional experimentation at the drift scale would add confidence to the approach taken.”

The Panel reviewed the impacts of five potentially disruptive processes on the Yucca Mountain repository. The Panel concurred with DOE findings in the TSPA-VA that impacts of earthquakes would be minor as would the impacts of volcanism on offsite groups. The Panel also agreed with DOE's analysis that nuclear criticality was highly improbable and, if it occurred, only modest increases in offsite doses would be expected. However, the Panel was not satisfied with DOE's analysis of human intrusion. They stated that the scenario in which the waste generated from an intruding borehole was driven downward into the SZ was not realistic and analytical treatment of transport within the saturated zone was potentially non-conservative. The particular concern with the transport model was the assumption that radioactive material was distributed over a wide area at the top of the SZ. This would not be the case with the selected drilling intrusion scenario. The Panel noted that a regulatory basis for analyzing human intrusion had not been established by either NRC or EPA at the time when the TSPA-VA calculations were made. The approach taken on the climate change in the TSPA-VA was judged to be reasonable, in-so-far as temporal variations in precipitation are concerned. The Panel noted that the U.S. Geological Survey disputed the manner in which the variation in precipitation was translated into infiltration rates into the repository but the Panel took no position on that issue.

Two potentially non-conservative approaches used in the TSPA-VA were identified by the Peer Review Panel, namely:

- Long-term performance of Zircaloy cladding on spent fuel
- Buildup of radionuclides in soil irrigated with contaminated groundwater

With regard to cladding performance, the Panel stated that additional failure mechanisms including (1) pitting and crevice corrosion, (2) hydride-induced embrittlement and cracking, and (3) unzipping of the cladding due to secondary phase formation when the UO_2 fuel is converted to various alteration products in a moist, oxidizing environment all need to be experimentally investigated. Until such work is completed and the expected cladding longevity can be substantiated, the TSPA-VA assumptions about the ability of the cladding to act as a significant barrier are not defensible.

The Panel observed that irrigation water was assumed in the TSPA-VA to be deposited on the soil for only one year prior to intake by the receptor via various soil-related pathways. In reality irrigation can continue for thousands of years and an equilibrium concentration for each nuclide will be established in the soil which is higher than that based on only a one-year exposure period. In addition, the assumption that iodine is rapidly washed through a soil column is not supported by field observations which show considerable holdup in the surface layers.

The Panel also identified three factors which were believed to treated with significant conservatism in the TSPA-VA including:

- Transport through penetrations in the waste package
- Retention of radionuclides in spent fuel alteration products
- Potential sorption of technetium and iodine in the UZ and SZ

The Panel felt that the modeling of the transport of radionuclides from failed waste packages through pits, cracks or crevices was not realistic since no significant retardation was included. Since this assumption is not consistent with expected physical reality, better methods are required to analyze the movement of radionuclides within and from the failed waste packages.

Any UO_2 in spent fuel packages which is exposed to moist air is expected to be converted to secondary uranium minerals such as schoepite within a few hundred years after waste package and cladding failure. It has been experimentally established that neptunium would be incorporated into the alteration products and, consequently, Np release would be controlled by the dissolution rate of these alteration products. While this process was not included in the TSPA-VA base case, it was cursorily examined in a sensitivity analysis (DOE98, Volume 3, Section 5.5.3). No impact was shown over the first 10,000 years or after about 700,000 years because releases are dominated by other nuclides for those time periods. However, at 100,000 years, the dose rate is reduced by about a factor of 10 when solubility of Np from the alteration products is considered.

No sorption of technicium or iodine (the major contributors to dose over the first 10,000 years) on geologic materials was considered in the TSPA-VA. However, the Peer Review Panel cited field observations, such as those of Straume et al. (STR96), taken near the site of the Chernobyl nuclear power plant accident suggesting that radioiodine may be retarded in soil surface layers. The Panel did not cite any instances where technetium was retarded but suggested that the issue should be reviewed on the basis, for example, of measurements near the Chernobyl site.

In addition to these general conclusions, the Panel provided detailed comments on all of the component models used in the TSPA-VA including the UZ flow, thermohydrology, near-field geochemical environment, waste package degradation, fuel cladding as a barrier, waste form degradation, radionuclide mobilization, UZ transport, SZ flow and transport, biosphere, and disruptive events. Recurring themes were the need for additional data and improved models to produce a credible and defensible LA.

7.3.4.3 Review by the U.S. Nuclear Waste Technical Review Board

The Nuclear Waste Technical Review Board (NWTRB; see Section 4.4 of this BID) also critiqued the TSPA-VA (TRB99). The Board stated that they had identified no features or processes which would disqualify the Yucca Mountain site but felt that DOE should give serious attention to replacing the high-temperature design evaluated in the TSPA-VA with a ventilated low-temperature design where waste package surface temperatures were maintained below the boiling point of water. Such a change should significantly reduce the uncertainties involved in attempting to analyze complex coupled thermal-hydraulic and thermal-mechanical, and thermal-geochemical interactions within the repository.

The NWTRB also expressed concerns as to whether the amount of work required to support a technically defensible decision on Yucca Mountain could be completed on DOE’s proposed schedule which calls for a site recommendation decision by 2001. This is a matter of particular concern, since the Board stated that expert elicitation should not be used as substitute for data gathering at the site or in the laboratory. Areas where additional factual input is required include waste package performance (e.g., resistance to stress-corrosion cracking), and the magnitude and distribution of seepage into the repository.

The Board also stressed the need for long-term scientific studies assuming the site is ultimately found to be suitable and construction is approved. These scientific studies should include selected aspects of both natural and engineered barriers.

In summary, the Board agreed with DOE “that Yucca Mountain continues to merit study as the candidate site for a permanent geologic repository and that work should proceed to support a decision on whether to recommend the site to the President for development. ... The Board supports continuing focused studies of both natural and engineered barriers at Yucca Mountain to attain a defense-in-depth repository design and to increase confidence in predictions of repository performance."

7.3.5 NRC Total System Performance Assessments

7.3.5.1 Background

To support it licensing responsibilities, the NRC is developing the capability to review DOE's TSPA in support of a License Application, if the Yucca Mountain site is found to be suitable for disposal. The Commission staff, like DOE, is iteratively developing TSPA modeling capability based on evolving information and insights concerning factors that affect repository system performance. Development of the TSPA methodology is independent of DOE's effort, and the DOE and NRC TSPA models and codes differ in detail.

The NRC's strategic planning calls for early identification and resolution, at the staff level, of TSPA issues before receipt of an LA, if the Yucca Mountain site is found to be suitable for disposal. The principal means for achieving this goal is on-going, informal, pre-licensing consultation in which performance issues are identified and discussed, and issue resolution is sought. Resolution of issues is sought at the staff level before formal licensing reviews, but issues may be raised and considered again in the licensing process.

To implement its goals, the NRC has focused its pre-licensing work on issues most critical to the post-closure performance of the proposed repository; these have been designated as Key Technical Issues (KTI). To facilitate dialog with DOE concerning resolution of the KTIs, the NRC has established Issue Resolution Status Reports (IRSR) to serve as the primary mechanism through which feedback to DOE concerning KTIs and KTI subissues will be expressed and documented. The IRSRs address acceptance criteria for issue resolution and the status of resolution. Updating revisions of the IRSRs will be issued periodically as progress is made in resolution of the KTIs and their subissues.

One of the Key Technical Issues identified and discussed in an IRSR is Total System Performance Assessment and Integration (TSPAI). The NRC has, to date, issued the original version of the IRSR on this topic in April 1998 and Revision 1 in November 1998 (NRC98). As basis for its review of the DOE TSPA and development of its own TSPA methodology, the staff has adopted the hierarchical structure of performance assessment factors shown in Figure 7-41.

This performance factor structure was used to develop the NRC TSPA code structure (e.g., TSP 3.x.y) illustrated in Figure 7-42. This code structure can be compared to DOE's TSPA-VA code structure shown in Figure 7-36.

The IRSR on total system performance assessment and integration identifies and describes the key subissues for this topic as follows:

- "Demonstration of the Overall Performance Objective. This subissue focuses on the role of the performance assessment to demonstrate that the overall performance objectives have been met with reasonable assurance. This subissue includes issues related to the calculation of the expected annual dose to the average member of the critical group and the consideration of parameter uncertainty, alternate conceptual models, and the results of scenario analysis.

- Demonstration of Multiple Barriers. This subissue focuses on the demonstration of multiple barriers and includes: (1) identification of design features of the engineered barrier system and natural features of the geologic setting that are considered barriers important to waste isolation; (2) description of the capability of barriers to isolate waste; and (3) identification of degradation, deterioration, or alteration processes of engineered barriers that would adversely affect the performance of natural barriers.

- Model Abstraction. This subissue focuses on the information and technical needs related to the development of abstracted models for TSPA. Specifically, the following aspects of model abstraction are addressed under this subissue: (i) data used in development of conceptual approaches or process-level models that are the basis for abstraction in a TSPA, (ii) resulting abstracted models used to perform the TSPA, and (iii) overall performance of the repository system as estimated in the TSPA. In particular, this subissue addresses the need to incorporate numerous features, events, and processes into the performance assessment and the integration of those factors to ensure a comprehensive analysis of the total system.

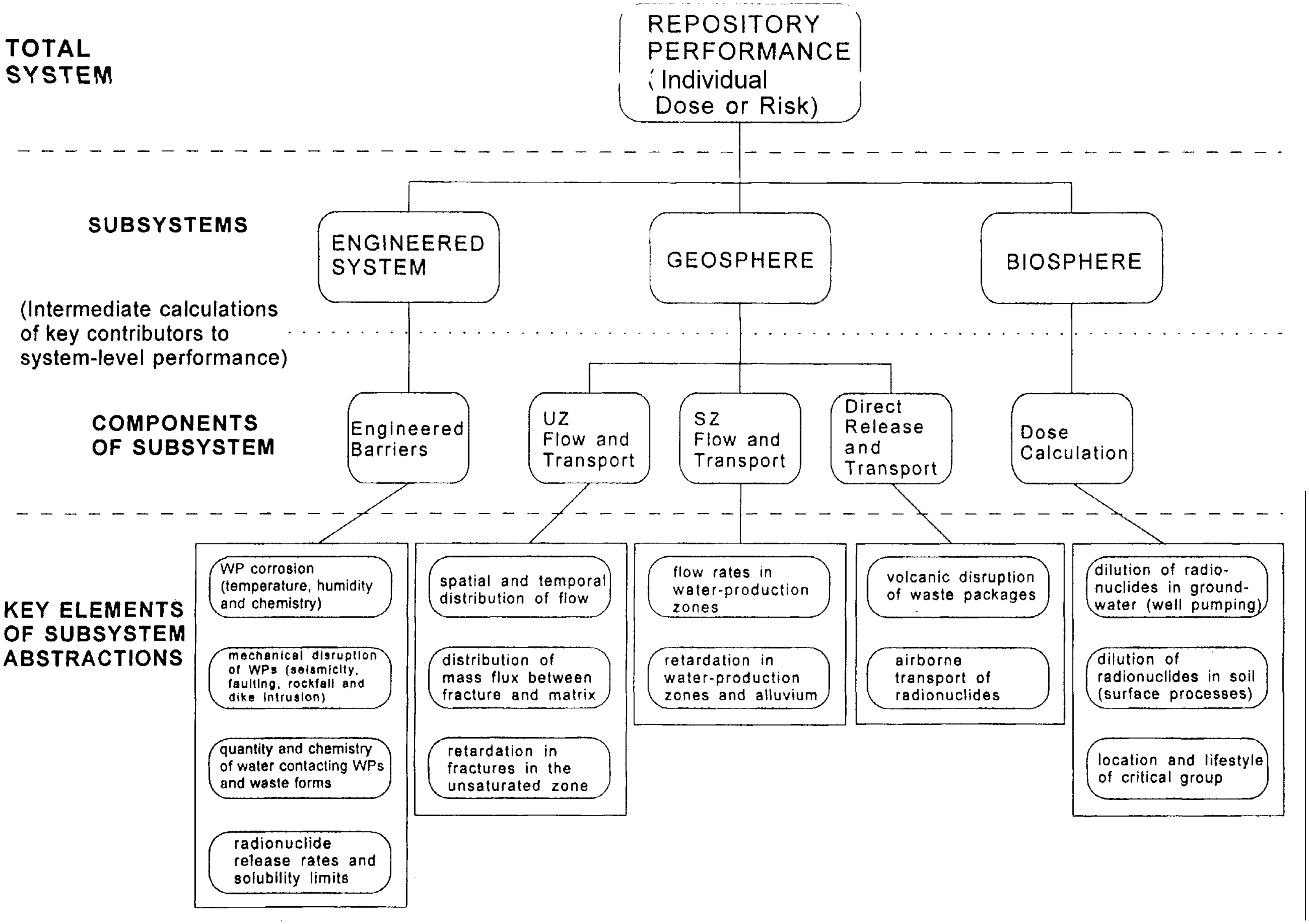


Figure 7-41. Structure of Performance Factors for NRC Performance Assessments (NRC98)

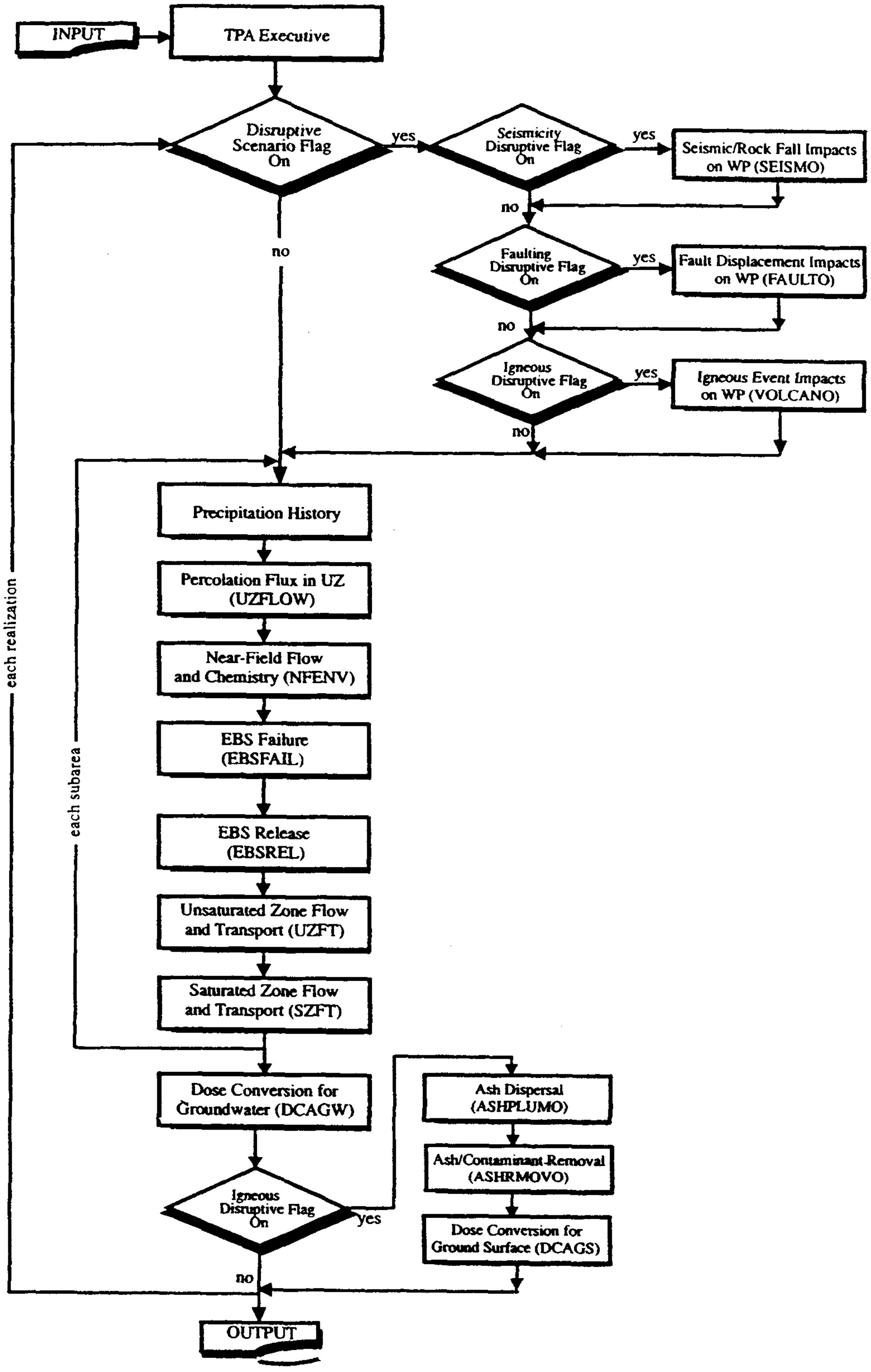


Figure 7-42. Structure of NRC Computer Codes for Performance Assessments (NRC98)

- Scenario Analysis. This subissue considers the process of identifying possible processes and events that could affect repository performance; assigning probabilities to categories of events and processes; and the exclusion of processes and events from the performance assessment. This is a key factor in assuring the completeness of a TSPA.

- Transparency and Traceability of the Analysis. This subissue emphasizes staff expectation of the contents of DOE's TSPA to support an LA. Specifically, it focuses on those aspects of the TSPA that will allow for an independent analysis of the results."

Details of acceptance criteria and review methods for the subissues related to demonstration of overall performance and demonstration of multiple barriers will be provided in the next revision of the IRSR for TSPAI. Details of criteria and review methods for model abstraction, scenario analysis, and transparency are included in NRC98.

7.3.5.2 NRC Development and Use of TSPA Models

The content and characteristics of NRC's TSPA models have, like DOE's, evolved over time as information and insights as basis for the models have developed. Current models, also like DOE's, are considered to be a snapshot in time from an on-going model-development process.

Under its Iterative Performance Assessment (IPA) program, NRC has adopted a phased approach to its TSPA modeling capability. Phase 1 used relatively simplistic models and was designed primarily to demonstrate capability to perform TSPA reviews as part of the licensing reviews. Phase 2 used significantly enhanced modeling methods to identify and assess factors of primary importance to repository system performance. Phase 3, which is still underway, uses more general and versatile computer codes to perform TSPA evaluations analogous to those performed by DOE.

Three versions of the Total-system Performance Assessment (TPA) code have been developed in Phase 3 of the IPA program. TPA 3.1.3 has been used to calculate mean doses for alternate conceptual models, and TPA 3.1.4 has been used for system-level sensitivity and uncertainty studies. The most recent version of the TPA code, 3.2, was used to provide feedback to DOE on the results of NRC's review of the TSPA (see Sections 7.3.2. and 7.3.3).

The most recently documented description of the NRC TPA codes is provided in NUREG 1668, which describes the characteristics and use of the 3.1.3 and 3.1.4 codes to perform sensitivity and uncertainty analyses for a proposed repository at Yucca Mountain (NRC99a). Characteristics of the TPA 3.2 code have not yet been documented, but results of its use were presented and discussed at the May 1999 DOE/NRC Technical Exchange (NRC99b) in which NRC staff provided feedback to DOE concerning results of their review of the TSPA-VA.

The TPA 3.1 and 3.2 codes have capability and flexibility comparable to those of the DOE codes for the TSPA-VA. As previously noted, the DOE and NRC codes differ significantly in detail, but both have capability to evaluate performance for alternative repository design features, natural system features, and disruptive scenarios, at a level of detail and characterization of uncertainty commensurate with the available information base. At present, the principal difference between the NRC and DOE performance assessment codes is that the NRC codes give considerable attention to disruptive events associated with seismicity and volcanism, while the DOE approach considers these phenomena to be unlikely to occur in ways that could affect repository performance. These differences are expected to be resolved as part of the issue resolution process.

Principal features of the NRC's Phase 3 performance assessment codes include the following:

- <u>Water infiltration into the subsurface</u>. Calculation of percolation flux takes into account the time history of climate change, variation of shallow infiltration with climate change, and the areal-average percolation flux at the repository horizon.

- <u>Near-field environment</u>. The near-field environment, which affects the waste package corrosion rate, is characterized in terms of drift wall and waste package surface temperatures, relative humidity, water chemistry, and water reflux during the thermal pulse phase.

- <u>Waste package degradation and EBS release</u>. Waste package failures depend on near-field conditions, corrosion mechanisms and rates, and mechanical effects such as rockfall. Radionuclide release from the EBS is calculated in terms of rate of release from the waste form, solubility limits, and transport mechanisms out of the EBS. No credit is taken in the base case for cladding performance as a barrier.

- <u>Transport in the UZ and SZ</u>. Time-dependent flow velocities in the UZ are calculated using the hydrologic properties of the major hydrostratigraphic units. Matrix and fracture flow are modeled. Radionuclide retardation on fracture surfaces is assumed not to occur, but sorption in the rock matrix is modeled. The conceptual hydrologic model for flow in the SZ assumes fracture flow in the tuff aquifer and matrix flow in the alluvial aquifer.

- Airborne transport for direct releases. NRC performance assessments include consideration of airborne releases from low-probability intrusive igneous events which cause direct release of waste package materials into the air. Factors considered include number of packages failed and quantities of radionuclides released, ash deposition patterns, and degradation of deposited, contaminated ash.

- Biosphere dose exposure scenarios. Dose evaluations are done for the average person in a designated receptor group. Two types of groups are considered: a farming community 20 km downgradient from the repository, and a residential community. The farming community is assumed to use contaminated ground water for drinking and agriculture; the residential community uses it only for drinking. Dilution of radionuclide concentrations in the ground water as a result of pumping is considered.

NUREG-1668 (NRC99a) reports the results of dose evaluations in which the base case TSP 3.1.4 model and 11 alternative conceptual models (such as including cladding credit) were used to calculate doses at 10,000 and 50,000 years for a receptor 20 km from the repository. The repository system conceptual design was similar to that used by the DOE in the TSPA-VA, but the corrosion-resistant inner package barrier was assumed to be Alloy 625. The annual base case mean peak total effective dose equivalent (TEDE) was projected to be 2.3 mrem at 10,000 years. Annual results for the alternative conceptual models ranged from a low of 0.012 mrem when cladding credit was taken to a high of 12.5 mrem when no radionuclide retardation was assumed. The range of results is shown as a bar chart in Figure 7-43.

As previously noted, the NRC presented its more recent TSP 3.2 results evaluations at the DOE/NRC Technical Exchange in May 1999 (NRC99b). Results presented for the ground-water dose using the NRC’s mean-values data set are shown in Figure 7-44, for 10,000 and 100,000-year dose rates. As can be seen, the 10,000-year dose rate is forecasted to be about 0.002 mrem/yr, and the 100,000-year dose is about 0.2 mrem/yr. These results can be compared to DOE’s TSPA-VA results, which indicated a 10,000-year dose rate of 0.04 mrem/yr and a 100,000-year dose rate of about 5 mrem/yr (see Figures 7-37 and 7-38). Reasons for differences in the NRC and DOE results are not readily apparent because parameter values and modeling approaches used by the two agencies differed markedly. For example, the DOE assumed cladding credit while the NRC did not; the NRC assumed an average of 32 juvenile waste package failures while the DOE assumed one; the DOE used three-dimensional modeling of UZ below the repository which suggested significant lateral diversion while the NRC used one

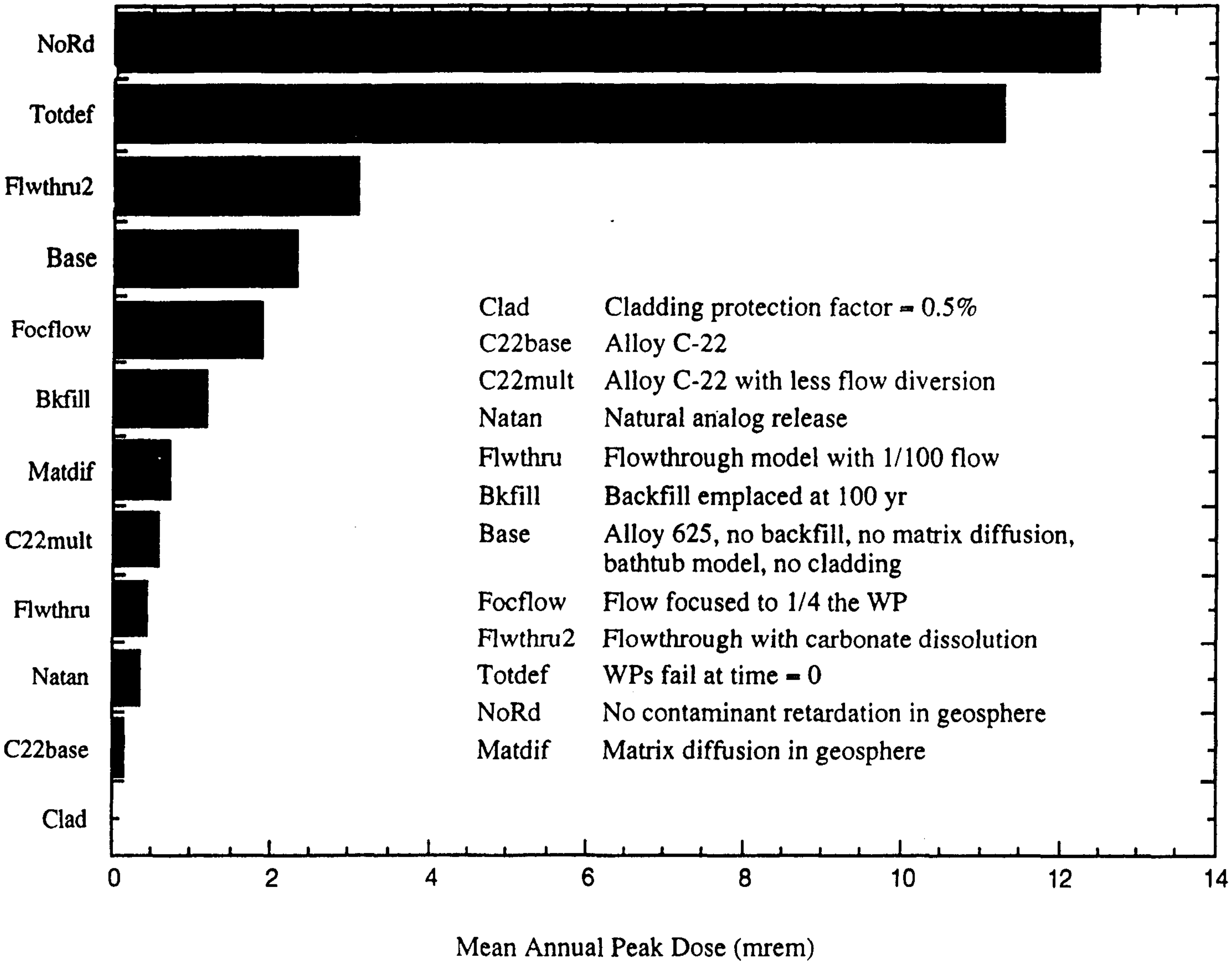
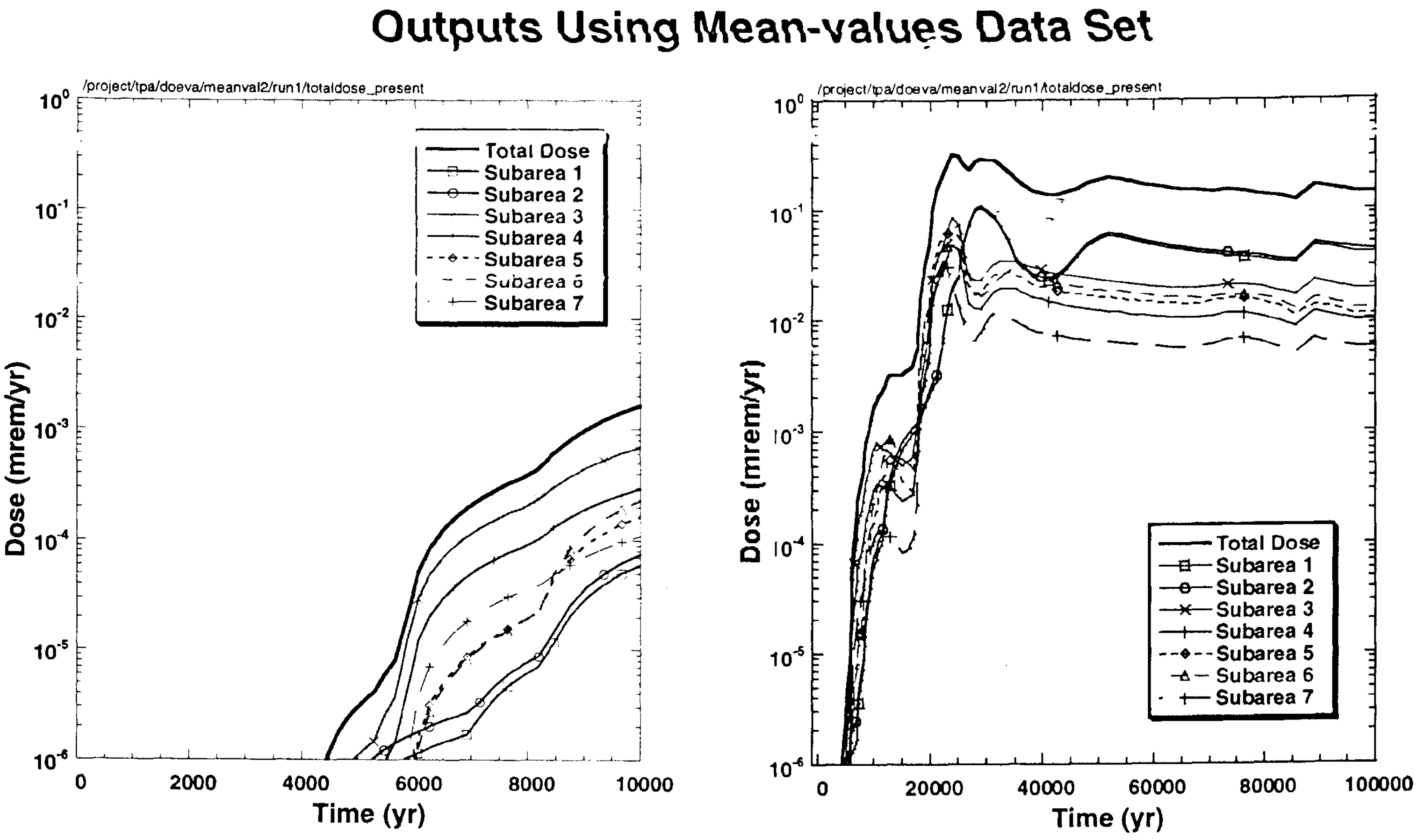


Figure 7-43 NRC TSPA Results for Alternative Conceptual Models (NRC99a)



10 kyr

100 kyr

Figure 7-44. NRC TSPA Results for Mean-Values Data Set (NRC99b) dimensional modeling with seven stream tubes and no lateral diversion. In addition, the NRC assumed dilution during pumping of contaminated ground water by thedose receptor, while DOE assumed this dilution did not occur.

7.3.5.3 Conservatism In The NRC Performance Assessments

As noted in Section 7.3.5.2, the NRC staff are independently developing performance assessment capability in order to be able to be able to perform comprehensive reviews of DOE's TSPA in the License Application. The NRC performance assessment capabilities and methods are, like DOE's, continuing to evolve. Documentation of NRC's parameter values, models and assumptions are not yet as comprehensive as DOE's; the most recent description of the NRC models and the results of their use was provided in the NRC/DOE Technical Exchange of May 27-29, 1999 (NRC99b). As reported during the Exchange, NRC's base-case performance evaluations using VA design parameters projected a 10,000-year dose rate of about 0.003 mrem/yr; DOE's base-case 10,000-year dose rate projection was 0.04 mrem/yr. Conservatisms in NRC's performance parameters, models, and assumptions, as indicated by information provided at the Technical Exchange, are summarized below.

Performance Parameters

NRC presentations at the May 1999 Technical Exchange indicated that "mean values" of the performance parameters were used for the base case performance assessments. Values of some of the parameters were presented, but comparisons with DOE are difficult because of differences in modeling approaches and parameters used. In general, NRC's use of "mean values" appears to correspond in concept to DOE's use of "expected values". Values of parameters used by NRC for precipitation and infiltration were, for example, similar to those used by DOE.

Performance Models

Key features of NRC's performance assessment modeling approach that are indicative of conservatism include the following:

- Impacts of igneous events, seismic rock falls, and fault displacements on waste packages were included in the models. Seismicity impacts were included in the base case evaluations; volcanism and faulting impacts were treated separately.

- No credit was taken for spent fuel cladding as an engineered barrier. Half of the spent fuel in a failed waste package was assumed to be exposed, wetted, and a source for release of radionuclides.

- Transport of radionuclides in the unsaturated zone from the repository to the water table was assumed to occur vertically, with no effect of matrix diffusion or sorption on fracture surfaces. This assumption is similar to that made by DOE in the TSPA-VA.

- Radionuclide transport in the saturated zone was assumed to occur via four pathways through fractured tuff and alluvium. Transport in the tuff occurred only via fractures, with flow rates between 50 and 500 m/yr. Flow velocities in the alluvium were assumed to be between 3 and 5 m/yr, and radionuclide retardation was assumed to occur.

- Dilution of radionuclide concentrations in ground water as a result of pumping by the dose receptor was assumed to occur (the dilution factor was not stated). This is a non-conservative modeling feature in contrast with DOE's assumption that such dilution does not occur.

Conservative Assumptions

Conservative assumptions in the NRC performance assessments described at the May 1999 Technical Exchange (NRC99b) included the following:

- Thirty-two waste packages were assumed to be defective at the time of emplacement. Rates and mechanisms of degradation and radionuclide release for these and other packages that fail were not described, however.

- The mean value of the localized corrosion rate for the Alloy 22 corrosion resistant material in the waste package was stated to be 2.5 E-4 m/yr. This is a factor of 100 higher than experimental values cited in EPRI's IMARC-4 report (EPR98) and in DOE's VA Technical Support Document (DOE98a).

Detailed comparison of NRC and DOE performance assessment conservatisms is not possible because the modeling approaches and parameters used differ significantly. In general, it appears that, in comparison with DOE, NRC's approach produces a larger radionuclide source term (e.g., as a result of assuming no cladding credit), but compensates for it by assuming that dilution occurs during pumping. The net result is that the results of NRC's performance assessments reported at the May 1999 NRC/DOE Technical Exchange agree with DOE's TSPA-VA results within an order of magnitude.

7.3.6 EPRI Total System Performance Assessments

7.3.6.1 Background

The nuclear power utilities have for many years maintained oversight of the OCRWM program in DOE because of their contracts with the Department concerning its responsibilities for receipt and disposal of commercial spent fuel. Technical contributions to the oversight are provided by EPRI in programs that are selected and guided by the utilities. EPRI maintains peer capability to review and comment on DOE's program activities and to independently perform performance assessments and other analyses of the type done by the Department within the OCRWM program.

EPRI has performed independent total system performance assessments in parallel with DOE's efforts. A report on EPRI's TSPA concepts and methods was first issued in 1990 (EPR90), and TSPA reports were subsequently issued in 1992, 1996, and 1998 (EPR92, 96, 98). The EPRI studies have kept pace with the DOE efforts, making use of the evolving repository design concepts, data bases, and modeling methods. The EPRI Phase 4 report, issued in November 1998 (EPR98) parallels the DOE's TSPA-VA report (DOE98) and uses the VA design.

The overall goal of the EPRI assessments is to provide an "...independent assessment of the performance of the potential repository site, identifying fatal flaws in the site itself, in the engineering design, or in the licensing program, so that the decision makers in the utility industry can judge the likelihood of potential outcomes of the licensing process and take appropriate action" (EPR96).

7.3.6.2 EPRI's TSPA Technical Approach

EPRI uses a logic tree approach to performance assessment modeling. The EPRI TSPA code is termed the Integrated Multiple Assumptions and Release Calculations code (IMARC). The logic tree approach, illustrated in Figure 7-45, represents uncertain inputs to the TSPA calculations as nodes in a tree, with branches from a node indicating alternative models or parameter values for that input and the weight associated with that model or parameter value. In contrast, the DOE TSPA code structure (Section 7.3.2.2) and the NRC approach (Section 7.3.4) use a central processor (e.g., the RIP code for DOE), which is fed information from codes for the various repository performance factors.

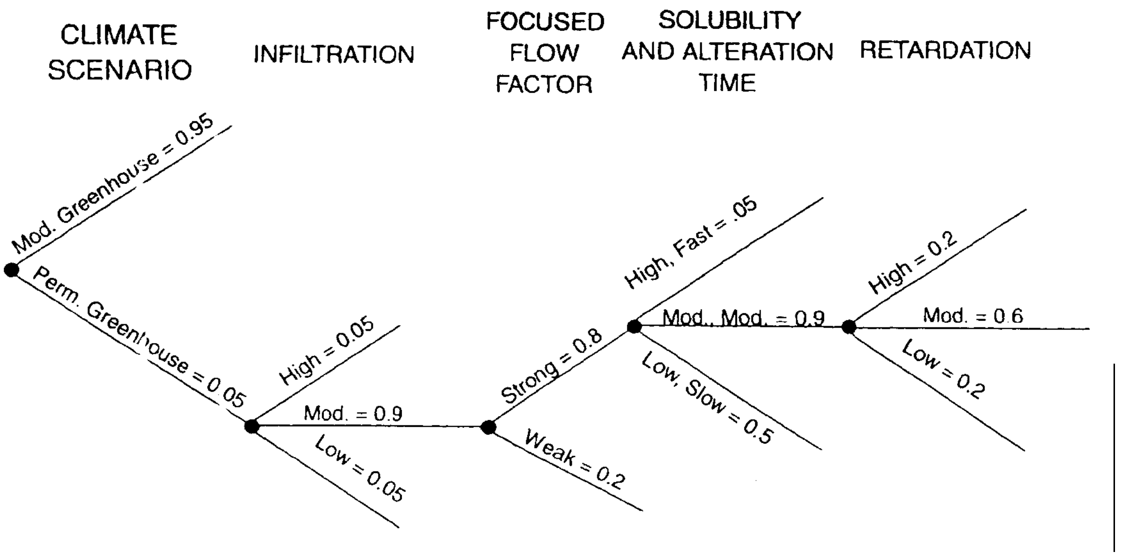


Figure 7-45. EPRI's IMARC Logic Tree (EPR98)

All TSPA methods include models for essentially the same performance factors, e.g., climate, infiltration, waste package performance, etc. They differ, however, in the details of how they model the performance factors and in their assignment of values for uncertain performance parameters. For example, the DOE assumed three climate conditions for the TSPA-VA, with precipitation spanning the range 170 to 540 mm/yr; in contrast, the EPRI interpreted the historic climate data to indicate two future climate conditions, with precipitation spanning the range 150 to 220 mm/yr.

Other key features of the EPRI Phase 4 TSPA modeling approach are outlined below. As for DOE, details of models and parameter characterization have evolved in accord with evolution of the data bases for performance assessment. Because the modeling approaches used in IMARC-4 were similar to those used in IMARC-3, the IMARC-4 report (EPR98) did not repeat technical details of modeling that were discussed in EPR96.

Climate

As indicated above, EPRI's interpretation of available data concerning past and possible future climate conditions led to an estimate that the long-term average precipitation should be between 150 and 220 mm/yr, a much narrower range than used by DOE in the TSPA-VA. EPRI believes the DOE precipitation values are based on ostracode species assemblages found in Minnesota and Washington, rather than on specific plant taxa calibrated near Yucca Mountain.

Infiltration

The basic IMARC net infiltration model is a one-dimensional finite difference code that incorporates source and sink terms for surface infiltration, uptake of water by plants, and drainage from the root zone to the deep subsurface (which is net infiltration). For Phase 4, the runoff features of the model were revised as a result of recent data. As a result, the net infiltration for current climate conditions increased from the Phase 3 (1996) value of 1.2 mm/yr to 7.2 mm/yr. The full glacial climate value increased from 2.9 to 19.6 mm/yr. (DOE's TSPA-VA values showed similar increases in comparison with TSPA-95 values.) The TSPA-VA results are higher than the Phase 4 results because the DOE assumed a precipitation rate of 300 mm/yr as compared to EPRI'sassumption of 195 mm/yr for a full glacial climate.

Near Field Conditions

For IMARC-4, EPRI developed a model and analytic solution which describes heat transfer and fluid flow in the near field in terms of a uniform disk-shaped heat source located in a moist, unsaturated, porous medium. Large-scale convective gas flow and countercurrent flow of water and vapor were assumed to occur. Heterogeneity of the repository's geohydrologic regime was represented by what was termed "focused flow, and "hot" and "cool" zones of the repository were characterized. The objective of the modeling was to estimate that fraction of the waste package inventory that is wetted; results indicated that the maximum fraction of the waste packages that are wetted is 0.24. In contrast, DOE's expected values in the TSPA-VA for waste packages with seeps were about 0.5 during superpluvial conditions and about 0.33 during the extended periods associated with long-term average climate (DOE98, Volume 3, Figure 4-3).

Waste Package Performance

The waste package performance model used in IMARC-4 differed significantly from that used in IMARC-3 because of improved understanding of the repository environment and corrosion processes, and because the reference corrosion resistant material (CRM) was changed from Alloy 825 to Alloy 22. The basis for characterizing corrosion rates was changed from Weibull distributions[1] to recently-obtained corrosion data and the results of DOE's expert elicitation on waste package performance. Corrosion rates were characterized for various environmental conditions, e.g., humid air or water dripping onto the package, and for various corrosion mechanisms, including crevice corrosion of the Alloy 22, which is anticipated to represent the mechanism for most-rapid penetration of the CRM. Results for the VA waste package design (see Section 7.2) show that, in the absence of drips onto the package, penetration would not occur for more than one million years. When drips do contact the packages, penetration by general corrosion is predicted not to occur for about 30,000 years. Under adverse conditions, the carbon steel outer wall could be penetrated in only 300 years, and the Alloy 22 inner wall could be penetrated by crevice corrosion, which is conservatively assumed to occur during the time period during which the waste package temperatures are greater than about 80°C. The EPRI estimates that "hot" waste packages would remain above the 80°C threshold for crevice corrosion for about 3,000 years. For "cold" waste packages this period would be reduced to about 200 years. The EPRI notes in IMARC-4, as did the DOE in the TSPA-VA, that the data base for estimating Alloy 22 corrosion rates is currently quite limited.

Source Term Parameters

Source term parameters discussed in IMARC-4 include radionuclide sorption, solubility, release from the waste form, and waste form alteration. Values for these parameters were changed in IMARC-4 in comparison with IMARC-3 because of recent data additions. The computer code COMPASS, Version 2.0, which is a compartment model for predicting radionuclide release rates from the engineered barrier system (EBS) into the near-field rock, was used in IMARC-4. The Compass 2.0 code models EBS features, such as waste form, canister corrosion products, backfill, and rock fractures, as compartments. It accounts for time-dependent cladding degradation, modes of water contact with the waste package, and modes of water transport through the waste package interior (overflow or through-flow).

Discussions of source term parameters in IMARC-4 addressed the following:

- New values of sorption coefficients for sorption of radionuclides on corrosion products (principally iron oxides) were presented for cases where recent data differ from results of a prior expert elicitation by more than a factor of five.

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[1] A Weibull distribution is a function used to describe the fraction of waste packages which have failed as a function of time based on mean container lifetime, threshold failure time and failure rate at the mean lifetime.

Median values for the actinides are in the range 5-10 m3/kg; the median value for Np is 0.1 m3/kg.

- Extensive discussion was presented on the validity of the two-orders-of-magnitude reduction in the solubility of Np in the TSPA-VA in comparison with TSPA-95. The EPRI analyses basically concurred with the action, which was based on re-assessment of prior data and additions to the data base for solubility values. The solubility of neptunium is important to prediction of doses after 10,000 years, when neptunium is the principal contributor to dose.

- Extensive discussion was provided concerning thin films surrounding spent fuel undergoing dissolution. The EPRI concluded that the TSPA-VA approach was a "sensible, but non-unique first step in attempting to derive more realistic radioelement solubility constraints from laboratory tests." The EPRI recommended additional modeling and laboratory tests to establish lower, more realistic solubility constraints.

Flow and Transport in the Unsaturated and Saturated Zones

The flow and transport models used in IMARC-4 were the same as those used in Phase 3. Values used for parameters were revised, however, as a result of recent insights concerning conceptual modeling of the UZ and SZ and continuing integration of field and theoretical studies.

The IMARC-4 UZ hydrology model accounts for transient, variably-saturated flow and advective-dispersive transport in a coupled dual-porosity-dual-permeability regime, from the base of the repository to the water table. Radionuclide sorption can occur both in the fractures and in the rock matrix. In the SZ, the model takes into account three-dimensional advective-dispersive transport of the radionuclides during down-gradient migration. The SZ model can handle matrix diffusion, radionuclide sorption and daughter-product ingrowth.

The repository footprint can be divided into subregions, each of which constitutes the top of a UZ hydrologic column. Input variables such as infiltration rates can therefore be varied over the area of the repository. The model assumes that there is no lateral coupling between the columns and that the system is isothermal, so that no coupling to the energy equations is needed.

Once the radionuclides reach the water table, they can advect, disperse, sorb, diffuse into or out of the matrix, and decay within the three-dimensional SZ. Ground water flow in the SZ is assumed to be representative of long-term steady-state conditions. The bulk hydraulic conductivity of the fractured rock mass is assumed to be representative of an equivalent porous medium, which may be anisotropic.

IMARC-4 discusses the impact of recent determinations that the net infiltration rate is much higher than originally believed, and the discovery of bomb-pulse Cl-36 at repository depths, on conceptual modeling of the UZ. It also discusses the impact of current lack of data for the SZ on uncertainty in the flow paths and dilution factors for the SZ. It notes that IMARC-3 asserted that overall dilution for the SZ was about a factor of ten, and that this value is retained in IMARC-4 and corresponds to the base case value used by DOE in the TSPA-VA. It also discusses dilution for a small radionuclide plume, such as would result from a single package failure, and asserts that the dilution factor for this situation would be on the order of 100,000.

Biosphere

The EPRI's IMARC analyses use a probabilistic model to estimate radiation doses. The model has three basic parts: probabilistic modeling of releases from the repository, characterization of dose conversion factors for the biosphere pathways and the nuclides of interest, and characterization of the dose receptor. In IMARC-4, EPRI used a farming critical group and the water-only pathway for their base case. Other possible dose circumstances (e.g., all pathways) were also evaluated. The critical group was assumed to be located 5 km from the boundary of the repository, i.e., at the boundary for release to the accessible environment as defined by 40 CFR Part 191.

The hypothetical critical group was assumed to extract ground water from the point of highest contamination in the contaminant plume, and to use this contaminated water for all of their food and water needs for their entire lifetime. Dose conversion factors were based on ICRP definitions of dose established in 1991 and on IAEA recommendations for metabolism of the elements established in 1994.

7.3.6.3 Results of IMARC-4 Dose Evaluations

The EPRI's IMARC-4 analyses produced base case results for conditions and assumptions outlined above, and also produced results for a wide range of sensitivity analyses. The EPRI base case results are shown in Figure 7-46. These results were obtained assuming that 0.01% of the waste packages had failed at emplacement (i.e., one package) and that 0.1% failed soon after emplacement (i.e., 1,000 yr). These early failures may be caused by manufacturing defects, construction errors, or emplacement mishandling. The EPRI modeling assumes no corrosion failures during the initial 10,000 years while the DOE modeling assumes that 17 waste packages will fail by corrosion during this period. Thus, the EPRI assumption for total waste package failures (juvenile plus corrosion) is 11 while the equivalent DOE assumption is 18.

The dose receptor was assumed to be an average member of a farming community located 5 km from the repository, and the doses are the result of exposure only via the ground water pathway. When all exposure pathways were included, the dose rate variations as a function of time were similar to those shown in Figure 7-46, but about a factor of ten higher. This indicates that, for the EPRI modeling approach for the critical group, the drinking water contribution to dose is minor in comparison with the agricultural and other pathways.

Comparison of Figure 7-46 with the results of the DOE TSPA-VA analyses, Figure 7-39, shows that the dose rates at various times are generally similar (e.g., DOE projects a dose rate at 10,000 years of 0.04 mrem/yr; EPRI projects 0.08 mrem/yr), and the sources of dose are similar, i.e., Tc-99 and I-129 are dominant in the near term and Np-237 is dominant in the long term. In the EPRI results, Figure 7-46, the decrease in dose rate over the interval 60,000 to 100,000 years is the result of depletion of the Tc-99 and I-129 inventories for release from the repository.

EPRI IMARC-4 results are compared to DOE’s TSPA-VA results and NRC’s TSP 3.2 results in Section 7.3.7.

7.3.6.4 Conservatism In The EPRI Performance Assessments

As indicated in Section 7.3.6.2, the EPRI approach to total system performance assessments differs markedly from those used by DOE and NRC. As a result, direct comparison of EPRI conservatism with that of DOE and NRC is neither possible nor appropriate. In general, the IMARC-4 report (EPR98) suggests that EPRI seeks to be as realistic as possible in all aspects of its assessment efforts. For example, EPR98 criticizes the DOE interpretation of data concerning past climates as being too conservative, observes that the assumption of an early package failure is arbitrary, and notes that the EPRI and TSPA-VA approaches to modeling of fracture /matrix interactions in the saturated zone differ markedly.

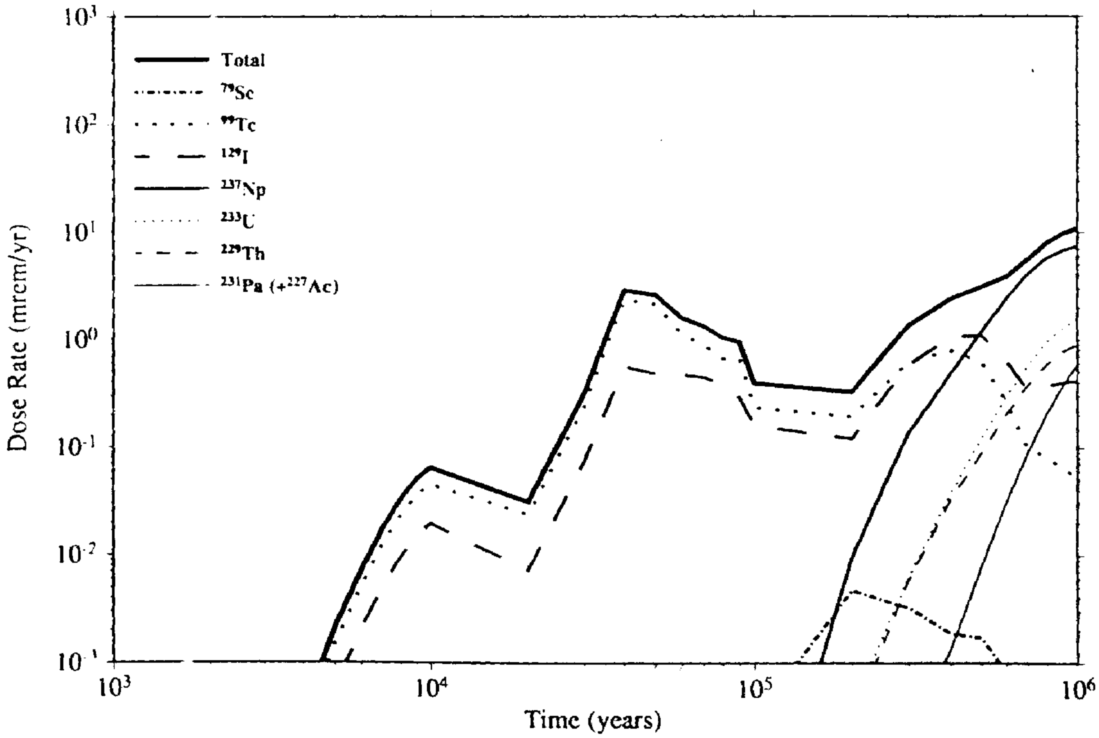


Figure 7-46. Results of EPRI's IMARC-4 Dose Evaluations (EPR98)

In contrast to DOE's adoption of expert opinion as the basis for waste package material corrosion rates, EPR98 includes a comprehensive effort to develop parametric models of corrosion behavior on the basis of available data. Like NRC, the EPRI IMARC-4 analyses take no credit for spent fuel cladding as a barrier. However, in contrast to NRC's bathtub model, EPRI uses a flow-through model for water entry to and exit from the interior of a failed waste package. This is similar in concept to DOE's approach, which assumed that radionuclides are instantaneously released to the EBS from the wetted waste form.

The IMARC-4 report, EPR98, includes a discussion which compares the IMARC-4 and TSPA-VA results. The report states:

> *"We observe that the magnitude of the doses estimated by IMARC Phase 4 are in general agreement with those in the TSPA-VA (within an order of magnitude for all time periods). This agreement can be considered quite close, given that the models, level of abstraction, and input parameters for particular FEPs [features, events, and processes] are considerably different between the two analyses. Whether this is simply fortuitous or speaks to the robustness of the combined*

> *analyses is not altogether clear. It may be that one particular combination of conservatisms (and potential non-conservatisms) in one TSPA effort were, on the whole, balanced by a different combination of conservatisms/nonconservatisms in the other TSPA analysis. There is certainly some evidence for this.*
>
> *In the end, this independent comparison of TSPA approaches for the proposed Yucca Mountain repository provides further confidence that the major FEPs controlling the overall safety of the facility have been identified."*

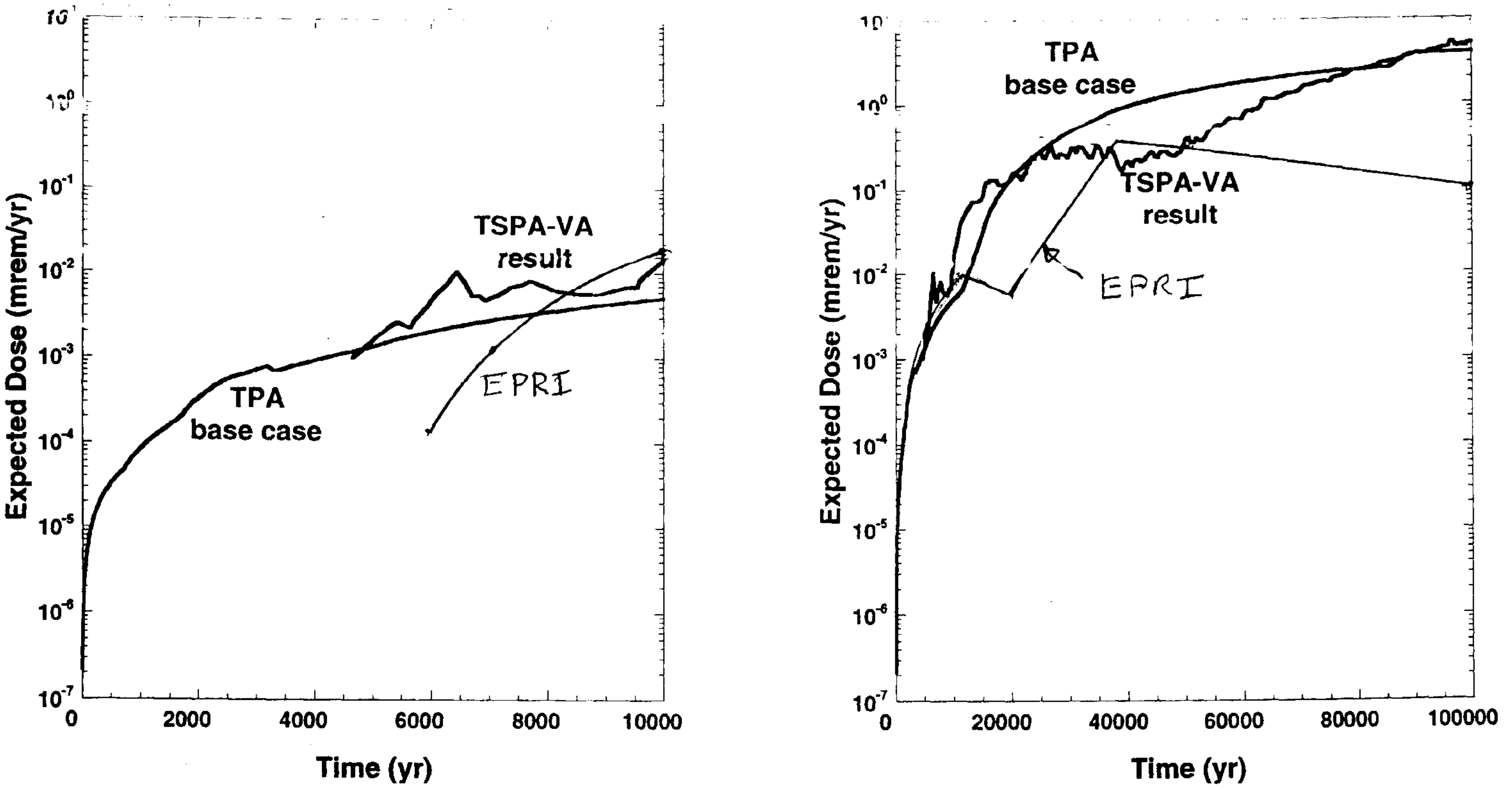
7.3.7 Comparison of DOE, NRC, and EPRI TSPA Results for the VA Repository

Although the TSPA models, assumptions, and parameter values used by DOE, NRC and EPRI differed greatly, each of the TSPA evaluations discussed above (DOE's TSPA-VA, NRC's TSP 3.2, and EPRI's IMARC-4) has as its basis the VA repository design concept, key features of which are the waste package design (an outer wall of carbon steel and an inner wall of Alloy 22), and an areal heat loading of 85 MTU/acre. Despite widely different modeling concepts, and with only the principal design features of the repository and the existing data base as the basis for commonality of the analyses, the results of the three TSPA efforts are quite similar, as shown in Figure 7-47.

In Figure 7-47 the EPRI results are decreased by a factor of ten in comparison with the actual results because the EPRI dose receptor was assumed to be located only 5 km from the repository. This location, in comparison with the 20 km distance assumed by DOE and NRC, would not have achieved the SZ radionuclide concentration reduction as a result of dilution that was assumed for the DOE and NRC analyses. Decreasing the EPRI results by a factor of 10 therefore puts all results on essentially the same basis with respect to the SZ dilution factor.

The similarity of the three sets of TSPA results may be the fortuitous consequence of offsetting assumptions. For example, DOE's TSPA-VA took credit for cladding performance as a barrier but took no credit for dilution during pumping; NRC's assumptions were the opposite of these.

Conversely, the similarity may be due to the dominant influence on results of performance factors for which the three analyses made similar assumptions, e.g., those concerning future climate conditions and early waste package failures. For all analyses, the dose rate results at 10,000 years are dominated by radionuclide releases from packages that were assumed to fail relatively soon after repository closure, and by the highly mobile Tc-99 and I-129 isotopes whose



10,000 yr

100,000 yr

Figure 7-47. Comparison of DOE, NRC, and EPRI Performance Assessment Results (derived from NRC99b) arrival at the dose receptor location is not significantly affected by assumptions concerning phenomena along the UZ and SZ pathway.

After EPA and NRC post-closure radiation protection standards for a possible repository at Yucca Mountain are established, opportunities for differences in assumptions concerning the dose receptor and biosphere pathways will be narrowed. Similarly, the need for assumptions concerning performance parameter values will be reduced by future additions to the data base. However, alternative TSPA modeling approaches can and will be maintained.

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