early Quaternary time. In a process that continues today, numerous small shifts in the positions of channels of ephemeral washes occurred during the Quaternary, as shown by the distribution of various types of Quaternary alluvial deposits (Hoover et al., 1981).

Deep entrenchment, low rates of erosion, and present topographic divides make it unlikely that the largest probable climatic change, from arid to semiarid, would cause a significant change in the location or the size of the drainage system at Yucca Mountain. Such climatic changes would not produce long-term water impoundments closer than Death Valley, which is 30 to 40 kilometers (20 to 25 miles) away.

There is no evidence at Yucca Mountain of surface-water impoundments formed by landslides. Eolian sands may have clogged some drainages at Yucca Mountain during early Quaternary time, but such sands are very permeable and also easily eroded. No evidence of water impoundment by eolian sands is known.

Conclusion

Surface-water systems in the region and at the Yucca Mountain site have changed little during at least the last several hundred thousand years of the Quaternary Period. The expected effects of predicted climatic changes on geohydrologic processes are not significant; no new water impoundments (lakes) nor significant changes in surface drainage are expected. No adverse effects on waste isolation are likely to result from climatic changes in the surface-water systems in the next 100,000 years. Therefore, the evidence indicates that this favorable condition is present at Yucca Mountain.

(2) A geologic setting in which climatic changes have had little effect on the hydrologic system throughout the Quaternary Period.

Evaluation

Evidence of climatic changes during the Quaternary comes from the geologic and plant-fossil records. A variety of types of deposits of Quaternary age occur in the region, including debris flows, fluvial sand sheets, eolian dunes, and coarse fluvial deposits (Hoover et al., 1981; Swadley, 1983). These units represent various environments of deposition that in turn reflect, in part, fluctuating climatic conditions. Although specific climates cannot be defined, the evidence is consistent with an arid to semiarid climate (Hoover et al., 1981). In addition, climatic changes can be inferred from the development of various landforms and rocks in the area and from the occurrence of three regional unconformities.

Vegetative covers varied in type during the past 45,000 years, as indicated by variations in the assemblages of plant macrofossils contained in pack-rat middens. These variations reflect changes in climate, in the sense that the assemblages are indicators of the effective moisture available at the time the plants were growing. Examinations of pack-rat middens show that, at different times during the last 45,000 years, the regional vegetative cover varied from a well-developed juniper woodland to modern desert scrub at intermediate elevations of about 1,200 to 1,800 meters (4,000 to 6,000 feet), and from a subalpine conifer woodland, to a pinyon-juniper woodland, and to a woodland-desert scrub mosaic at higher elevations above 1,800 meters (6,000 feet) (Spaulding, 1983).

Evaluation for pluvial climates

Quaternary hydrologic conditions that differed the most from modern conditions probably were those that occurred during several pluvial periods of presumably wetter conditions. These pluvials alternated with interpluvials, periods during which climatic and hydrologic conditions were similar to those of today. Most evidence for estimating the nature of pluvial climates in the region is based on pluvials of late Wisconsin age; in southern Nevada, there is virtually no evidence for estimating early Wisconsin and pre-Wisconsin paleoclimates, except for the qualitative evidence of landforms, paleosols, and unconformities. Therefore, the reconstruction of climates that existed before late Wisconsin time in southern Nevada is tenuous. However, some evidence indicates that the climate in Nevada during each of the pluvials was similar; therefore, an analysis of the late Wisconsin pluvial climates and their hydrologic effects provides a sound basis for estimating the maximum effects that occurred during the entire Quaternary. For example, on a global scale, similar climatic conditions probably prevailed during each of the major glacial epochs that occurred during the Quaternary (Spaulding, 1983). Mifflin and Wheat (1979) suggest that the pluvial lakes of Lahontan (Wisconsin) age that occurred in central and northern Nevada were generally as large as the lakes of pre-Lahontan times. This suggestion is based primarily on the absence of evidence of older lake shorelines at higher elevations (although such evidence may have been destroyed by erosion). On the other hand, the latest Wisconsin pluvial is believed to have been wetter and warmer than the one that preceded it during the Wisconsin full-glacial time (Spaulding et al., 1984). Because of the higher temperatures, greater precipitation would have been required to maintain lake levels at elevations similar to those at which lakes occurred during earlier, cooler pluvials.

Winograd et al. (1985) hypothesize that a progressive and continued uplift of the Sierra Nevada and Transverse ranges during the Quaternary may have led to a long-term trend of increasing aridity in Nevada. Huber (1981) suggests that the Sierra Nevada have risen about 1,000 meters (3,300 feet) since the Pliocene, and Hay (1976) postulates a rise of 1,800 meters (5,900 feet) in the last 4.5 million years. The rising mountain ranges would have produced a rainshadow effect that would have modified the distribution and the amount of precipitation in Nevada and resulted in increasing aridity (Winograd et al., 1985).

Most investigators believe that, even during pluvials, semiarid conditions persisted on the valley floors of southern Nevada and that conditions no wetter than subhumid prevailed on the highest mountains (Winograd and Doty, 1980; Thompson and Mead, 1982; Spaulding et al., 1984; and Mifflin and Wheat, 1979). A review of literature relevant to pluvial climates in southern Nevada and studies of pack-rat middens in the region indicates that, at the time of the global glacial maximum during late Wisconsin time (18,000 $\pm$ 3,000 years ago), temperatures in the region averaged 6 to 7°C (11 to 13°F) below the modern mean annual temperature (Spaulding, 1983; Spaulding et al., 1984). Average annual precipitation was probably 20 to 30 percent above the modern value. Winter precipitation was 60 to 70 percent above the modern average, while summer precipitation was 40 to 50 percent below. Mifflin and

Wheat (1979) also concluded that full-pluvial climates in Nevada did not differ greatly from modern climates. From the results of climatologic and hydrologic analyses, they estimate that the statewide full-pluvial mean annual temperature was about 3°C (5°F) lower and the mean annual precipitation was about 68 percent higher than modern values; they further conclude that the absence of physiographic evidence of pluvial lakes in southern Nevada supports the concept of aridity in that area during pluvial climates.

Although the estimated departures from modern annual and seasonal precipitation may appear substantial on a percentage basis, they are minor when calculated on an absolute basis. If the percentage departures presented by Spaulding (1983) are applied to estimates of the average precipitation for 1964 through 1981 at an elevation of 1,200 meters (4,000 feet) in the vicinity of Yucca Mountain, the estimated precipitation for full-glacial near-pluvial conditions is as follows:

	Estimated precipitation, mm (in.)	
	1964-1981	Near-pluvial
Annual	150 (5.9)	195-210 (7.7-8.3)
Cool season (Oct.-Apr.)	108 (4.2)	173-184 (6.8-7.2)
Warm season (May-Sep.)	42 (1.6)	21-25 (0.8-1)

The estimates for 1964-1981 are based on maps presented by Quiring (1983).

After the full-glacial (Wisconsin-maximum) pluvial, a trend toward warmer and drier conditions began (Spaulding et al., 1984). The drying trend was interrupted by a pluvial period that occurred during the latest Wisconsin time (12,000 to 10,000 years ago) and early Holocene (10,000 to 8,000 years ago) times. The climate during this pluvial probably differed substantially from the preceding full-glacial pluvial and from modern conditions. Compared with conditions during the Wisconsin maximum, the average annual temperatures during the latest Wisconsin pluvial were 4 to 6°C (7 to 11°F) higher, and the average annual precipitation was probably greater. The greater rainfall occurred during both the winter and the summer half years. Compared with modern conditions, average annual temperatures were probably only about 2°C (4°F) lower, and the average annual precipitation may have been as much as 100 percent greater. These conclusions are based on the distributions of vegetation assemblages during the late Wisconsin and early Holocene; they are consistent with predictions of climatic change and with evidence of fluctuations of lake levels in the Great Basin (Spaulding et al., 1984).

If precipitation during the latest Wisconsin pluvial had been 100 percent greater than modern, the average annual precipitation at that time would have been about 300 millimeters (11.8 inches). Such a relatively high rainfall would have been required to maintain the high stands of Searles Lake and Lake Lahonton under the warm (near-modern) average temperature that probably prevailed (Spaulding et al., 1984). This estimate of the precipitation increase is the highest of any reported in the studies reviewed by Spaulding

(1983) or identified elsewhere. Thus, it provides a conservative estimate that can be used to examine potential climatic effects on the hydrologic system at Yucca Mountain.

Evaluation for hydrologic effects

Climatic changes resulting in pluvial conditions during the Quaternary probably had the following effects on the hydrologic system: increased recharge, increased altitude and gradients of the water table; upgradient shifts in discharge points; and changes in surface-water drainage systems. Field evidence in the immediate vicinity of Yucca Mountain is not yet available to determine the size of these effects.

During the pluvial climates of the Quaternary, ground-water recharge rates were probably higher than modern rates. Claassen (1983) reports that carbon, hydrogen, and oxygen isotope data indicate that major recharge occurred in the area at the end of Pleistocene and through early Holocene time. Probably the recharge came principally from snowmelt and occurred as downward infiltration of surface runoff in major washes (Claassen, 1983), such as Fortymile Wash. During the span of this recharge period, two distinct climatic changes occurred, one at about the Wisconsin maximum (18,000 ± 3,000 years ago) and one in the latest Wisconsin (12,000 to 10,000 years ago) (Spaulding et al., 1984). The specific pluvial climatic conditions in the Yucca Mountain area that resulted in these recharge conditions are being evaluated by analyzing plant macrofossils in pack-rat middens in the area.

An increase in ground-water recharge would have been accompanied by increases in moisture flux through the unsaturated zone in some portions of the ground-water basin. The mechanisms and controls on the rates and distribution of recharge are not well known, either for modern or for pluvial conditions; therefore, the magnitudes of recharge during the last half of the late Wisconsin are not known at this time, but they may have been substantially greater than those of modern recharge (Czarnecki, 1985). Investigations to assess this condition are underway.

The increased flux may have been sufficient to affect the potential for developing perched-water conditions in the unsaturated zone and to modify the hydrologic system in the underlying saturated zone. However, hydrologic tests and measurements of core samples of unsaturated rock units underlying Yucca Mountain indicate that the fracture and matrix permeability is generally high enough to transmit water not only at the low modern fluxes (less than 0.5 millimeter (0.02 inch) per year, as discussed in Section 6.3.1.1), but also at the higher fluxes postulated for pluvial times. Thus, the increase in recharge that is postulated for pluvial climates may not have affected significantly the potential for developing perched-water conditions. However, it is likely that the increased flux may have affected the hydrologic conditions in the saturated zone (see evaluation of potentially adverse condition 2).

An evaluation of the effects of Quaternary climatic changes on the altitude of the water table is difficult, because tectonic and erosional as well as climatic factors could have affected the position of the water table.

Some evidence of Quaternary hydrologic conditions is found in the region around Yucca Mountain. Even though the evidence is generally not within the flow system underlying Yucca Mountain, the interpretations from this evidence can be used as general indicators of the effects of Quaternary climatic changes on the regional hydrologic systems, as described in the following paragraphs.

Jones (1982) examined cores of fine-grained alluvium from a borehole in Frenchman Flat (located in the Ash Meadows ground-water basin) for mineralogic evidence of former higher water tables. In the interval 0 to 50 meters (0 to 165 feet) above the present water table, the alluvium contains an abundance of zeolites and smectite clays with expanded basal spacings and relatively uniform clay hydration properties. These conditions suggest possible former saturation, but they may also be related to differences in the primary environments of deposition. Jones (1982) concludes that the relative uniformity of clay hydration is consistent with an interpretation that the water table has been within approximately 50 meters (165 feet) of its present position for a long time, perhaps throughout most of the Quaternary.

Death Valley and the Amargosa Desert are the principal discharge areas for both the Ash Meadows ground-water basin and the Alkali Flat-Furnace Creek Ranch ground-water basin (Winograd and Thordarson, 1975; and Waddell, 1982) as shown in Figure 6-17. Winograd et al. (1983) reported that calcite veins in the Ash Meadows discharge area have been estimated to be 0.8 to 1 million years old by uranium-thorium dating techniques. Thus, these regions probably were ground-water discharge areas during most of the Quaternary. Within the Ash Meadows ground-water basin, however, discharge from the carbonate aquifer occurred as much as 14 kilometers (9 miles) northeast (up gradient) of the modern discharge line during the Pleistocene, and the water table may have been 50 meters (165 feet) higher than its present elevation (Winograd and Doty, 1980). In central Frenchman Flat, 58 kilometers (36 miles) northeast of Ash Meadows, the maximum water-table elevation in the carbonate aquifer probably did not exceed 30 meters (100 feet) above the modern level (Winograd and Doty, 1980). This estimate, based on theoretical studies, is consistent with the 50-meter (165-foot) maximum increase estimated in the Devils Hole area of the Ash Meadows ground-water basin. Preliminary modeling indicates that during pluvials, similar upgradient discharge points and increased water table altitudes could develop in the future in the Alkali Flat-Furnace Creek Ranch ground-water basin in which the Yucca Mountain site is located (Czarnecki, 1985).

Quaternary climatic changes probably produced cyclic fluctuations in both the altitude of the water table and the positions of the ground-water discharge points of the Ash Meadows basin, but Winograd and Doty (1980) postulate a net direction of change in both of these hydrologic conditions during the Pleistocene Epoch. They suggest that the highest water-table position occurred in the early Pleistocene and that a net downgradient migration of discharge sites and a net decline of the water table occurred from early to late Pleistocene time. They attribute these changes to the progressive integration of the Amargosa Valley and the Death Valley watersheds, coupled with periodic faulting along the modern spring lineament in Ash Meadows. A long-term trend of increasing aridity, if it occurred,

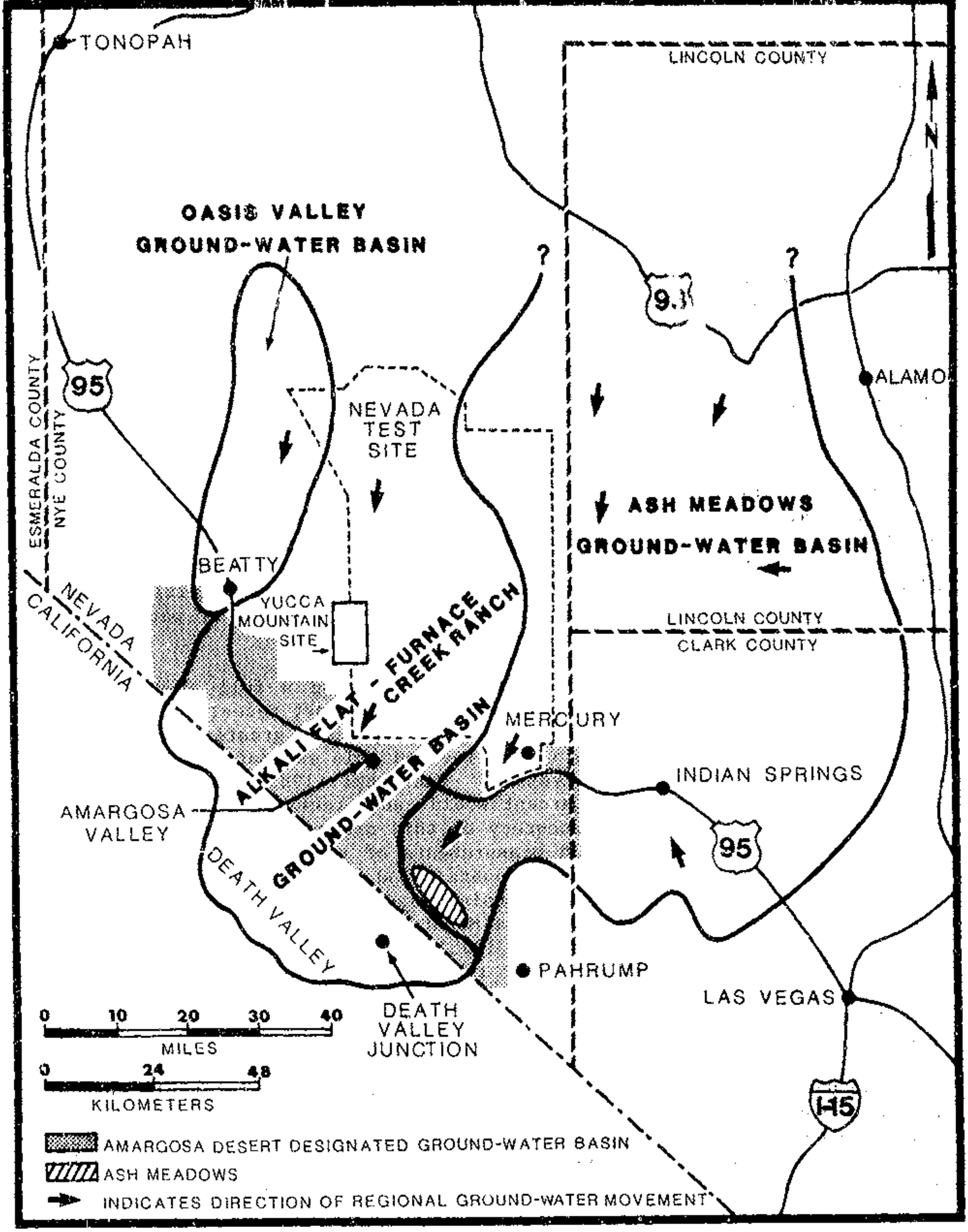

Figure 6-17. Location of Yucca Mountain site with respect to the relevant basins of the Death Valley ground-water system. The Amargosa Desert ground-water basin is a governmentally administrated area designated by the State engineer in order to prevent over appropriation of ground-water resources. Modified from Waddell (1982) and information from the State of Nevada.

could also have contributed to these hydrologic changes. Similar changes would be expected to have occurred in the Alkali Flat-Furnace Creek Ranch ground-water basin.

In the tuff and alluvium of the Alkali Flat-Furnace Creek Ranch ground-water basin, no direct evidence has been observed for a water table that was higher during the Quaternary than it is now. Depth to water in the Yucca Mountain area is generally 500 to 750 meters (1,650 to 2,450 feet) (Robison, 1984). To estimate the effects of increased recharge on the altitude of the water table in the basin, a two-dimensional flow model (Czarnecki and Waddell, 1984) was modified and analyzed at various recharge rates. According to Czarnecki (1985), preliminary modeling has been able to simulate a maximum rise in water-table altitude within the Alkali Flat-Furnace Creek Ranch ground-water basin of 130 meters (430 feet) during pluvial conditions. This value of 130 meters (430 feet) resulted from assuming a 100-percent increase in precipitation over Yucca Mountain (probable maximum increase in next 10,000 years) which in turn was assumed to produce a recharge rate of 7.5 millimeters per year (0.29 inches) beneath the primary repository area.

The prediction of a 130-meter (430-foot) rise in the water table at Yucca Mountain in response to a 100-percent increase in precipitation during a return to pluvial conditions (Czarnecki, 1985) is highly uncertain and may be very conservative. The use of a two-dimensional model to simulate three-dimensional flow and uncertainty in appropriate boundary conditions for modeling are inherent sources of uncertainty in predictions of water-table altitudes.

The amount of increase in precipitation during a full pluvial is uncertain. Spaulding (1983) indicated that in the most recent full pluvial, precipitation was probably on the order of 50 percent greater than modern amounts, while Spaulding et al. (1984) revised this estimate to 100 percent above the modern precipitation values. Czarnecki (1985) assumed that a precipitation increase of 100 percent would cause recharge to increase by a factor of 15. To examine the accuracy of this assumption, modeled recharge estimates were compared to field measurements of recharge in an area with altitudes that are similar to Yucca Mountain and precipitation about 100 percent greater than that at Yucca Mountain today. This comparison suggests that the recharge estimates for Yucca Mountain may be too high by about two-thirds due to runoff (Czarnecki, 1985). No correction for runoff was applied to the recharge estimates for the preliminary predictions of water-table changes at Yucca Mountain; the effect would be to decrease the effective recharge to much less than the computed volumes used in the analyses (Czarnecki, 1985).

Another source of uncertainty in the simulation of water-table changes during a pluvial period is the method used to simulate recharge in the modeled area. The largest baseline fluxes were assigned at the northern boundary of the modeled area and along Fortymile Wash. The flux multiplier of 15 times baseline flux was applied simultaneously to all areas.

Sensitivity studies by Czarnecki (1985), show that the resulting change in water-table position beneath the primary repository area was primarily caused by the increased flux simulated by applying the multiplier at Fortymile Wash. Although it is true that washes are likely to be sources of major recharge during wetter climatic periods, applying the same recharge multiplier over the entire modeled area is probably overly conservative because uplands are unlikely to experience increased infiltration relative to precipitation in the same proportion as washes.

A final source of uncertainty on the modeling of water-table rise is related to the system response time. The Czarnecki (1985) model is not time dependent; it implicitly assumes that recharge is instantaneous and that water-table response is instantaneous. The rate at which the water-table altitude would change in response to increased precipitation is unknown. This suggests that with the onset of a pluvial, it is uncertain how long it would take for changes in water-table altitude to occur.

With all of the above uncertainty on the effects of climatic changes on the hydrologic system, a conservative position is warranted for this favorable condition.

Conclusion

Yucca Mountain is in a geologic setting in which the maximum departures from modern climatic conditions during most of the Quaternary were probably not substantial. However, changes in the water-table altitude and possible modifications of flow paths to discharge areas cannot be ruled out. Therefore, the evidence indicates that this favorable condition is not present at Yucca Mountain.

6.3.1.4.4 Potentially adverse conditions

(1) Evidence that the water table could rise sufficiently over the next 10,000 years to saturate the underground facility in a previously unsaturated host rock.

Evaluation

Several lines of evidence indicate that the water table will not rise enough during the next 10,000 years to saturate a repository in the Topopah Spring welded unit beneath Yucca Mountain. Climatic changes and their effects on the regional ground-water system are discussed under favorable condition 2. The discussion that follows addresses the potential for a water-table rise beneath Yucca Mountain.

The proposed repository is closest to the water table at its northeastern edge. Here, the repository would be at an elevation of approximately 915 meters (3,000 feet), or approximately 185 meters (605 feet) above the present water table (altitude 730 meters (2,395 feet)). Therefore, the water table would have to rise about 185 meters (605 feet) before any part of the proposed repository would be flooded. As discussed in favorable condition 2, flow modeling (Czarnecki and Waddell, 1984; Czarnecki, 1985) suggests that the maximum rise in water-table altitudes during pluvial conditions is unlikely to exceed 130 meters (430 feet). Even if extreme pluvial conditions developed, the additional 55 meters (180 feet) should provide adequate assurance that the repository could not become saturated. It should also be noted that the repository midplane dips to the east so that the 185-meter (605-foot) distance is a minimum thickness for the unsaturated zone beneath the repository. Figure 6-4(A) in Section 6.3.1.1 shows that the average distance from the repository to the water table is about 250 meters (820 feet). In addition, Winograd et al. (1985) suggest there may be a long-term trend toward increasing aridity in the Yucca Mountain area.

Vitric pumice does not remain unaltered for long periods of time in the saturated zone (Hoover, 1968). Beneath the central portion of Yucca Mountain, nonwelded tuffs containing abundant vitric pumice occur at altitudes that range from 120 meters (400 feet) at boreholes USW H-5 and USW G-4 to 250 meters (820 feet) at borehole USW H-3 above the present water table. These altitudes are 24 to 120 meters (80 to 400 feet) below the repository horizon (Bish et al., 1984). Therefore, the rocks in the repository horizon were probably never below the water table, at least not for any substantial length of time.

The hydraulic conductivity of the densely welded, saturated Topopah Spring Member beneath Fortymile Wash is relatively high, approximately 1 meter (3.3 feet) per day (Thordarson, 1983) and may partly account for the very low hydraulic gradient in the saturated zone between Yucca Mountain and Fortymile Wash. An increase in recharge would cause an increase in hydraulic gradient approximately proportional to the increase in recharge; the gradient would be partly controlled by the distance to the discharge area. In areas where the gradient is now low, an increase in gradient would result in only small increases in hydraulic heads. In the Yucca Mountain area, the altitude of the water table is about the same (within 0.5 meter (1.6 feet) as the composite hydraulic potential of the upper few hundred meters of the saturated zone (Robison, 1984); the hydraulic potential may therefore be equated with the position of the water table.

An alternative approach for estimating potential changes in altitude of the water table is based on the following reasoning. In the discharge area near Alkali Flat and upgradient, the water table is within a few meters of the land surface. Therefore, a small increase in the hydraulic gradient would cause springs to develop upgradient. Approximately 15 kilometers (9.5 miles) north of Death Valley Junction, the hydraulic gradient is greater than it is immediately up and down gradient, which indicates rocks of lower permeability in this area. Springs would develop upgradient of this area if recharge increased appreciably, thereby permitting water to leave the groundwater system. If recharge increased enough (for example, three to four times the present rate) to cause springs to develop in these potential discharge areas (altitude 760 meters (2493 feet)), the water-level altitude at Well J-12 could be expected to increase in time to between 790 and 825 meters (2,590 and 2,700 feet). Because of the high transmissivity in western

Jackass Flats, the water level beneath most of the repository would also be 800 to 825 meters (2,625 to 2,707 feet), but the lowest part of the repository is estimated to be more than 900 meters (2,950 feet) above sea level.

Conclusion

There is no evidence that the water table was as high as the proposed repository level during the Quaternary Period, and it is very unlikely that climatic changes during the next 10,000 years could cause the water table to rise sufficiently to saturate the underground facility. Therefore, the evidence indicates that this potentially adverse condition is not present at Yucca Mountain.

(2) Evidence that climatic changes over the next 10,000 years could cause perturbations in the hydraulic gradient, the hydraulic conductivity, the effective porosity, or the ground-water flux through the host rock and surrounding geohydrologic units, sufficient to significantly increase the transport of radionuclides to the accessible environment.

Evaluation

Likely climatic changes over the next 10,000 years probably would be driven by increases in the global atmospheric concentration of carbon dioxide and by changes in the earth's orbit. In the near future Yucca Mountain might experience summer temperatures at least 3°C (5°F) higher and summer rainfall as much as 100 percent higher than today's value (Spaulding et al., 1984); these changes could be caused by increases in carbon dioxide concentrations. On the other hand, changes in the earth's orbit could eventually override the effects of carbon dioxide and lead to a glacial stage in about 23,000 years and culminate in a glacial maximum about 60,000 years into the future (Spaulding, 1983). Pluvial conditions, which may coincide with the glacial stage, but do not necessarily do so, are considered possible within the next 10,000 years.

As explained in the evaluation of favorable condition 2, conservative and preliminary computer modeling results by Czarnecki (1985) simulated a maximum increase of about 130 meters (425 feet) in water-table altitudes below the repository during a pluvial period. The minimum distance between the repository midplane and the water table is presently 185 meters (605 feet) in the northeastern corner of the primary repository area (See Figure 6-4). Over most of the primary area, the water table is more than 250 meters (820 feet) below the repository midplane. The uncertainty in the prediction of the 130-meter (425-foot) water-table rise is reviewed in the second potentially adverse condition above.

Even with the onset of pluvial conditions soon after repository closure, the response time for changes in hydrologic conditions and increases in water table altitude is likely to provide a lag time of many hundreds, and perhaps thousands of years before a maximum water-table altitude could occur, no matter what that maximum altitude would be. Furthermore, the retardation mechanisms that would be effective in both the saturated and unsaturated zone under conditions of higher flux and predominantly fracture flow, are likely to provide a factor of 100 (Sinnock et al., 1984) and perhaps a factor of 400 (Travis et al., 1984) increase in travel times for radionuclides over ground-water travel times. This argument suggests that there is a very low probability that climate changes in the next 10,000 years could be sufficient to induce significant increases in transport of radionuclides to the accessible environment.

Conclusion

The climatic changes that are possible during the next 10,000 years at Yucca Mountain may cause changes in the hydraulic gradient; changes in flux could alter the moisture content in the unsaturated hydrogeologic units; particle velocities in both the saturated and the unsaturated zones could increase if flux is greater; and the water-table altitude may increase. The extent of these changes is uncertain. However, these changes are not likely to significantly increase the transport of radionuclides to the accessible environment. Therefore, the evidence indicates that this potentially adverse condition is not present at Yucca Mountain.

6.3.1.4.5 Evaluation and conclusion for the climate changes qualifying condition

Evaluation

The effects of predicted climatic changes on geohydrologic processes are not expected to be large; no new lakes or significant changes in surface drainage are expected. Climatic conditions during most of the Quaternary Period probably did not depart substantially from modern conditions and probably had minor effects on the main features of the present hydrologic system. There is no evidence that the water table was as high as the proposed repository level during the Quaternary Period, and it is extremely unlikely that the water table will rise sufficiently to saturate the repository in the next 10,000 years. Considering the most extreme pluvial conditions and the maximum increase in water-table altitude beneath the repository, radionuclide travel times from the disturbed zone to the accessible environment should still be a factor of at least 100, and perhaps 400 longer than the ground-water travel times. This retardation estimate relies only on matrix diffusion as an agent for retarding radionuclide transport. It appears likely that the Yucca Mountain site will comply with the U.S. Environmental Protection Agency release limits under all possible climatic changes over the next 10,000 years.

Conclusion

Future climatic conditions during the next 10,000 years would not be likely to lead to radionuclide releases from a repository at Yucca Mountain greater than those allowable under the requirements specified in the postclosure system guideline (10 CFR 960.4-1, 1984). Therefore, on the basis of the above evaluation, the evidence does not support a finding that the site is not likely to meet the qualifying condition for postclosure climatic changes (level 3).

6.3.1.4.6 Plans for site characterization

Computer modeling efforts will be continued to gain a better understanding of factors controlling water-table altitudes in the Alkali Flat-Furnace Creek Ranch ground-water basin. Paleohydrologic, paleoclimatologic, and geologic studies will focus on the Yucca Mountain site to determine whether conclusive evidence for past water-table positions can be obtained. Further evolution of the conceptual model for flow in the unsaturated zone will lead to an improved definition of the relationship between precipitation, percolation rate, and recharge.

6.3.1.5 <u>Erosion (10 CFR 960.4-2-5)</u>

6.3.1.5.1 Introduction

The qualifying condition for this guideline is as follows:

<u>The site shall allow the underground facility to be placed at a depth such that erosional processes acting upon the surface will not be likely to lead to radionuclide releases greater than those allowable under the requirements specified in Section 960.4-1</u>.

The objective of the erosion guideline is to ensure that erosional processes will not degrade the waste-isolation capabilities of a repository site. In evaluating the potential effects of erosion on waste isolation, the thickness of overburden above the host rock is most important. The site should allow the underground facility to be placed deep enough to ensure that the repository will not be uncovered by erosion or otherwise adversely affected by surface processes.

The erosion guideline consists of three favorable conditions, two potentially adverse conditions, one disqualifying condition, and one qualifying condition. The evaluations reported below are summarized in Table 6-31 for all conditions except the disqualifying condition.

6.3.1.5.2 Data relevant to the evaluation

<u>Summary of available data</u>

The surficial geology of the Yucca Mountain area has been mapped (Scott and Bonk, 1984) from which the nature of erosional processes operating during the Quaternary Period can be interpreted. Measurements of the depth of stream incision in dated alluvial deposits and in tuff in the vicinity of Yucca Mountain have been made, and the maximum rates of stream incision have been calculated (USGS, 1984). Average erosion rates for Yucca Mountain

Table 6-31. Summary of analyses for Section 6.3.1.5; erosion (10 CFR 960.4-2-5)

Condition	Department of Energy (DOE) finding
FAVORABLE CONDITIONS	
(1) Site conditions that permit the emplacement of waste at a depth of at least 300 meters below the directly overlying ground surface.	The evidence indicates that this favorable condition is not present at Yucca Mountain: the preferred repository horizon cannot accommmodate all waste at depths greater than 300 meters within the primary repository area.
(2) A geologic setting where the nature and rates of the erosional processes that have been operating during the Quaternary Period are predicted to have less than one chance in 10,000 over the next 10,000 years of leading to releases of radionuclides to the accessible environment.	The evidence indicates that this favorable condition is present at Yucca Mountain: minimum depth to the repository is about 230 meters; there is only one chance in 10,000 of removing 5.5 meters (18 feet) of overburden in 10,000 years. Erosional processes are not expected to affect waste containment and isolation.
(3) Site conditions such that waste exhumation would not be expected to occur during the first one million years after repository closure.	The evidence indicates that this favorable condition is present at Yucca Mountain: a waste repository in Yucca Mountain would not be exhumed during the first one million years at the fastest credible erosion rate.
POTENTIALLY ADVERSE CONDITIONS	
(1) A geologic setting that shows evidence of extreme erosion during the Quaternary Period.	The evidence indicates that this potentially adverse condition is not present at Yucca Mountain: there is no observed evidence of extreme stream incision rates during the past 300,000 years; little change has been observed in Quaternary erosional processes.

Table 6-31. Summary of analyses for Section 6.3.1.5; erosion (10 CFR 960.4-2-5) (continued)

Condition	Department of Energy (DOE) finding
(2) A geologic setting where the nature and rates of geomorphic processes that have been operating during the Quaternary Period could, during the first 10,000 years after closure, adversely affect the ability of the geologic repository to isolate the waste.	The evidence indicates that this potentially adverse condition is not present at Yucca Mountain: no credible geomorphic process has been identified that could be expected to adversely affect the isolation capabilities of the proposed site in the next 10,000 years.
QUALIFYING CONDITION	
The site shall allow the underground facility to be placed at a depth such that erosional processes acting upon the surface will not be likely to lead to radionuclide releases greater than those allowable under the requirements specified in Section 960.4-1.	Existing information does not support the finding that the site is not likely to meet the qualifying condition (level 3): erosional rates and processes at Yucca Mountain during the Quaternary Period are expected to continue; about 2 million years is the minimum credible time to exhume the repository.

during the Quaternary Period have not been determined, because the field data necessary for such calculations are not yet available. The potential host rock in the Topopah Spring Member has been identified (Johnstone et al., 1984) and the thickness of overburden has been analyzed (Mansure and Ortiz, 1984). Water-table altitudes are available from Robison (1984).

Assumptions and data uncertainties

In evaluating the site against this guideline, the rates of stream incision in alluvium and tuff are assumed to represent the average rates of vertical erosion for the tuffs at Yucca Mountain. This assumption leads to over estimates of the probability of exhumation by erosion because the average rates of vertical erosion will always be much lower than stream-incision rates. It is also assumed that the erosional rates and processes operating during the Quaternary Period will continue during the postclosure isolation period. This assumption appears valid because climatic conditions are not likely to change significantly (Section 6.3.1.4), and local uplift or subsidence is not likely to be significant (Section 6.3.1.7).

6.3.1.5.3 Favorable conditions

(1) Site conditions that permit the emplacement of waste at a depth of at least 300 meters below the the directly overlying ground surface.

Evaluation

Figure 6-18 shows contours of the overburden thickness above the midplane of the repository envelope (45 meters (150 feet) thick) and the position of the cross section in Figure 6-19. Figure 6-19 shows profiles across Yucca Mountain at the 200- and 300-meter (656- and 984-foot) depths below the surface along an east-west cross section (Mansure and Ortiz, 1984). It also shows the depth of a plane representing the preferred horizon for the repository. This horizon is located in a portion of the densely welded Topopah Spring Member that contains less than 15 to 20 percent lithophysae and lies above the basal vitrophyre. In the primary area, on which site investigation has been focused, approximately 50 percent of the waste could be emplaced below 300 meters (984 feet). To emplace all the waste below 300 meters (984 feet) would require emplacement in the vitrophyre and lower units or the use of a higher thermal loading (i.e., placing the waste disposal containers closer together) than that currently used as a design basis. Other units deeper in Yucca Mountain have been considered as alternatives to the Topopah Spring Member (Johnstone et al., 1984).

Preliminary surface-mapping and borehole data suggest that the use of expansion areas adjacent to the primary area may allow the emplacement of additional waste below 300 meters (984 feet), while remaining within the part of the Topopah Spring Member that is relatively free of lithophysae (see Section 6.3.1.3, Figure 6-14). Further study of the areas adjacent to the primary area is necessary before their suitability can be established to the same degree of certainty that has been established for the primary area. There are no current plans to use the vitrophyre and the units below the Topopah Spring Member.

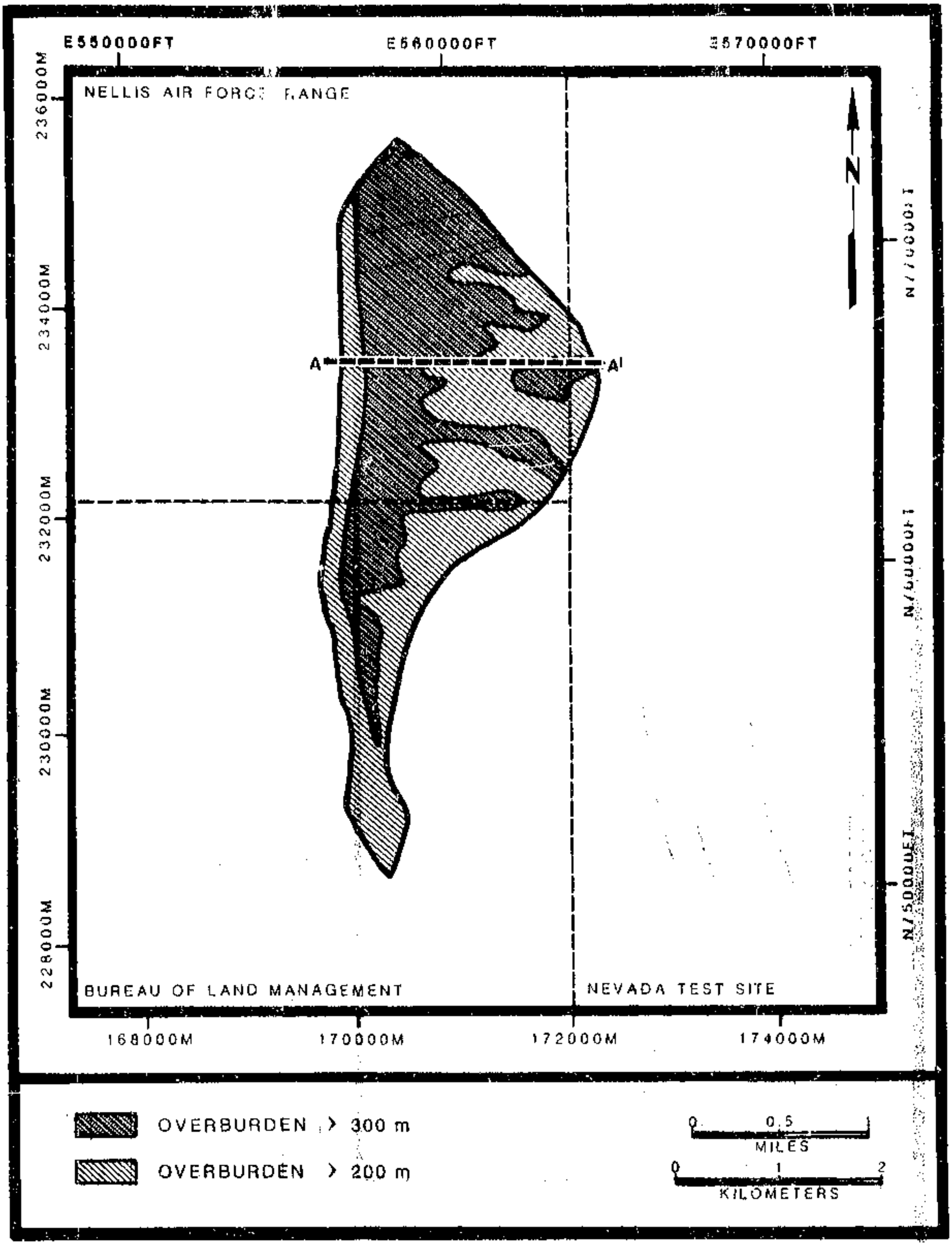

Figure 6-18. Contours of the overburden thickness above the midplane of the repository for primary repository area. See Figure 6-19 for cross section A-A'. Modified from Mansure and Ortiz (1984).

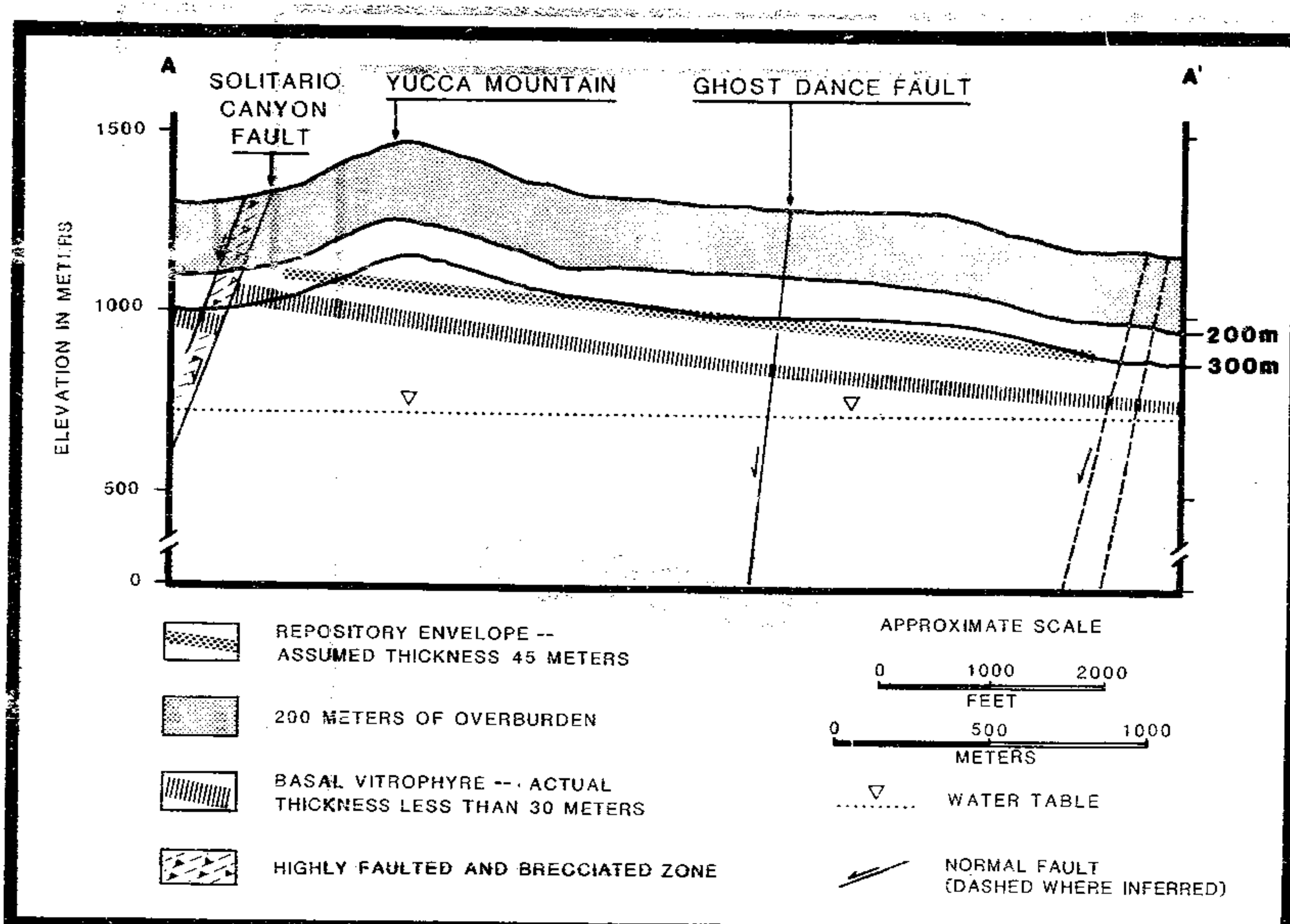

Figure 6-19. Profiles of the 200- and 300-meter (656- and 984-foot) depths below the surface of Yucca Mountain on schematic east-west cross section, labeled A-A' on Figure 6-18.

Conclusion

The data evaluated to date show that the potential host rock in the lower part of the Topopah Spring Member cannot accommodate all of the waste at depths greater than 300 meters (984 feet). Therefore, the evidence indicates that this favorable condition is not present at Yucca Mountain.

(2) A geologic setting where the nature and rates of the erosional processes that have been operating during the Quaternary Period are predicted to have less than one chance in 10,000 over the next 10,000 years of leading to releases of radionuclides to the accessible environment.

Evaluation

It is possible to postulate two mechanisms by which erosional processes operating at Yucca Mountain could adversely affect the potential for radionuclide releases to the accessible environment: (1) a gradual uncovering of the repository and (2) an alteration of the ground-water system.

The surface in the portion of the site that would contain the repository consists of densely to moderately welded tuff of the Tiva Canyon Member of the Paintbrush Tuff; the tuff dips 5 to 8° eastward, resulting in a relatively planar, eastward-sloping land surface. The welded tuff along the crest at the western edge of Yucca Mountain is resistant and essentially undissected by drainage channels, but to the east the Tiva Canyon Member is dissected by southeasterly draining channels with equilibrium profiles that are steeper than the dip of the tuff. Residual patches of the weakly consolidated Rainier Mesa Member of the Timber Mountain Tuff occur in the Tiva Canyon outcrop area (Scott and Bonk, 1984). Alluvium occurs in modern washes and fault valleys in the area.

The depth of stream incision has been measured by using dated stratigraphic horizons as reference points at several places in the vicinity of the site, and the maximum rate of incision has been estimated (USGS, 1984). Estimates based on two measurements in alluvium and one in the Tiva Canyon tuff show a mean rate of incision of 5×10^{-5} meter per year. The time spans represented by the measurements suggest that the average incision rate has been lower than 1×10^{-4} meter per year during the last 300,000 years. At a rate of 1×10^{-4} meter per year, erosion in the next 10,000 years would remove only 1 meter (3.3 feet) of overburden.

In order to affect hydrologic conditions in the vicinity of the site, erosion would have to cause a relocation of ground-water discharge to areas nearer to the repository site or expose rock units that would allow more infiltration. Erosion is unlikely to increase the potential for local infiltration, because the rocks in the overburden are already capable of passing fluxes well in excess of current and future percolation expected under the possible climatic changes during the next 10,000 years (favorable condition 2, Section 6.3.1.1). Therefore, at some locations all of the overburden that overlies the water table downgradient from the repository would have to be removed before the isolation potential of Yucca Mountain could be affected by erosion. Within 5 kilometers (3 miles) downgradient of the repository, this would require the removal of about 280 meters (920 feet) of overburden (Robison, 1984). At a rate of 1 x 10^{-4} meter per year, the time for erosion to this depth would be 2.8 million years.

From another perspective, the removal of 280 meters (920 feet) of overburden to the depth of the water table in 10,000 years would require an erosion rate of about 2.8 centimeters (1.1 inches) per year, which exceeds any rate known to have occurred anywhere on earth over any 10,000-year period. Using the measurements of stream incision (USGS, 1984), the probability of removal of 280 meters (920 feet) of overburden in 10,000 years is less than 1 chance in 1,000,000. This probability was derived from the Student's t distribution, computed for a mean incision rate of 0.5 meter per 10,000 years and a standard deviation of 0.3 with 2 degrees of freedom. The same method gives 1 chance in 10,000 over 10,000 years of eroding to a depth of 5.5 meters (18 feet).

Conclusion

Average stream-incision rates have been lower than 1 x 10^{-4} meters per year for the last 300,000 years. If continued at this rate over the next 10,000 years, erosional processes would be expected to remove only 1 meter (3.3 feet) of overburden. This amount could not adversely affect waste containment and isolation. The probability of loss of isolation due to erosion is less than 1 chance in 1,000,000 over the next 10,000 years. Therefore, the evidence indicates that this favorable condition is present at Yucca Mountain.

(3) Site conditions such that waste exhumation would not be expected to occur during the first one million years after repository closure.

Evaluation

The minimum thickness of the overburden above the underground facility is about 230 meters (750 feet) at the eastern edge of the primary repository area (see favorable condition 1). For about 50 percent of Yucca Mountain, the overburden is greater than 300 meters (984 feet). At an erosion rate of 1 x 10^{-4} meter per year, the time needed to uncover a repository at a minimum depth of 230 meters (750 feet) is 2.3 million years; for a depth of more than 300 meters (984 feet), it would take at least 3.0 million years.

Conclusion

If past average erosion rates continue in the future, a repository at Yucca Mountain would not be uncovered in the next 1 million years. Therefore, the evidence indicates that this favorable condition is present at Yucca Mountain.

6.3.1.5.4 Potentially adverse conditions

(1) A geologic setting that shows evidence of extreme erosion during the Quaternary Period.

Evaluation

The measured maximum stream-incision rates in the vicinity of the site are between 2.2×10^{-5} and 8.2×10^{-5} meter per year; these maximum rates are inferred by measuring the depths of incision in Quaternary, and in some instances Tertiary surfaces 160,000 to 10 million years old. The mean of these rates is 5×10^{-5} meter per year, which is much lower than the 1×10^{-4} meter per year that is used in the evaluation of the qualifying condition and in favorable conditions 2 and 3. Modern denudation rates at the site are not considered extreme, and evidence indicates that there were few or no periods of extreme erosion at the site during the past 300,000 years.

Conclusion

Average stream-incision rates during the past 300,000 years were not extreme, and there was little change in the patterns of erosional processes at the site during the Quaternary Period. Therefore, the evidence indicates that this potentially adverse condition is not present at Yucca Mountain.

(2) A geologic setting where the nature and rates of geomorphic processes that have been operating during the Quaternary Period could, during the first 10,000 years after closure, adversely affect the ability of the geologic repository to isolate the waste.

Evaluation

Geomorphic processes result when the combined effects of tectonic and climatic conditions create a local terrain that provides the potential energy for erosion. The rates of tectonism during the Quaternary are so low (Section 6.3.1.7) and the magnitudes of expected climatic changes are small enough (Section 6.3.1.4) that significant changes in geomorphic processes at Yucca Mountain are highly unlikely during the next 10,000 years. Because the estimated past and present rates of erosion have been shown to be incapable of affecting waste isolation for at least the next few million years, any credible change in these rates during the next 10,000 years would not adversely affect waste isolation.

Conclusion

No credible geomorphic process has been identified that could, in the next 10,000 years, adversely affect the isolation capabilities of the site. Therefore, the evidence indicates that this potentially adverse condition is not present at Yucca Mountain.

6.3.1.5.5 Disqualifying condition

The site shall be disqualified if site conditions do not allow all portions of the underground facility to be situated at least 200 meters below the directly overlying ground surface.

Evaluation

A repository at Yucca Mountain can be positioned so that all portions of the underground facility can be located below 200 meters (656 feet) and approximately 50 percent of the facility can be located at least 300 meters (984 feet) below the directly overlying ground surface (Mansure and Ortiz, 1984). The 200-meter (656-foot) overburden requirement is being used as a principal design constraint for locating the underground facility. According to stratigraphic data obtained during preliminary investigations at the Yucca Mountain site, the preferred interval of the densely welded tuff of the Topopah Spring Member (the zone with less than 20 percent lithophysae) is thick enough at depths greater than 200 meters (656 feet) to accommodate the underground facility (Figure 6-19).

Conclusion

The densely welded tuff of the Topopah Spring Member is sufficiently thick and deep for all portions of the underground facility to be located in the zone of low lithophysal content at least 200 meters (656 feet) below the directly overlying ground surface. Therefore, the evidence does not support a finding that the site is disqualified (level 1).

6.3.1.5.6 Qualifying condition

Evaluation

Geomorphic processes result from the combined effects of tectonic and climatic processes. The rates of tectonism are low (Section 6.3.1.7), and they are unlikely to induce changes in the erosional processes. As discussed in Section 6.3.1.4, the expected climatic changes are also unlikely to cause changes in erosional processes.

Measurements of stream-incision rates in the vicinity of Yucca Mountain suggest that the average incision rate has been lower than 1×10^{-4} meter per year during the last 300,000 years. The water table at some point down-gradient within 5 kilometers (3 miles) of the site would have to be uncovered by erosion before the isolation potential of Yucca Mountain could be affected. This would require the removal of about 280 meters (920 feet) of overburden, and, at expected erosion rates, would take about 2.8 million years. In the next 10,000 years, erosional processes are expected to remove only 1 meter (3.3 feet) of overburden from above the repository. Therefore, as shown by the measured depth of stream incision and dated alluvial materials, erosion could not uncover a repository at Yucca Mountain, nor could it alter the ground-water system sufficiently to adversely affect waste isolation.

For waste disposal in the unsaturated zone, the potential value of thick overburden should not be evaluated alone; equally important for an unsaturated zone repository may be the vertical distance from the repository to the water table. This thickness may bear more relationship to the waste-isolation capability of an unsaturated zone repository than does the thickness of the overburden.

Conclusion

The erosional rates and processes that have operated at Yucca Mountain during the Quaternary Period are very likely to continue for tens of thousands to millions of years into the future and will not adversely affect the waste isolation capabilities of the site. Therefore, on the basis of the above evaluation, the evidence does not support a finding that the site is not likely to meet the qualifying condition for postclosure erosion (level 3).

6.3.1.5.7 Plans for site characterization

During construction of the exploratory shaft at Yucca Mountain, walls of the shaft will be geologically mapped and photographed and the stratigraphic characteristics of lithologic units will be recorded. Field investigations will continue to improve the dating of Quaternary deposits and to better establish the local and regional geomorphic history of the Quaternary Period.

6.3.1.6 Dissolution (10 CFR 960.4-2-6)

6.3.1.6.1 Introduction

The qualifying condition for this guideline is as follows:

The site shall be located such that any subsurface rock dissolution will not be likely to lead to radionuclide releases greater than those allowable under the requirements specified in Section 960.4-1.

The objective of the dissolution technical guideline is to ensure that dissolution processes will not adversely affect the waste isolation capabilities of the site. The principal concern is that dissolution of the host rock will adversely affect the waste isolation capabilities of the site by creating new pathways for radionuclide migration to the surrounding geohydrologic system. The assessment of compliance with this guideline is to be based on evidence of dissolution in the geologic setting of the site during the Quaternary Period. The question of dissolution is not expected to be of concern at Yucca Mountain because the rock types present are considered to be insoluble.

The dissolution guideline contains one favorable condition, one potentially adverse condition, one disqualifying condition, and one qualifying condition. The evaluations reported in the following sections are summarized in Table 6-32.

6.3.1.6.2 Data relevant to the evaluation

Summary of the available data

The host rock at Yucca Mountain has been extensively studied by drillhole sampling in and around the exploration block (Heiken and Bevier, 1979; Sykes et al., 1979; Carroll et al., 1981; Spengler et al., 1981; Waters and Carroll, 1981; Bish et al., 1982; Caporuscio et al., 1982; Byers and Warren, 1983; Maldonado and Koether, 1983; Levy, 1984a,b; Scott and Castellanos, 1984; Spengler and Chornack, 1984; Vaniman et al., 1984). The mineralogic characteristics of the host rock are reviewed in a current summary report (Bish et al., 1984). Kerrisk (1983) provides a discussion of reaction-path calculations of volcanic-glass dissolution. The origin of lithophysal cavities in the tuffs has been reviewed (Byers et al., 1976; Lipman et al., 1966). No evidence of Quaternary dissolution fronts or other Quaternary dissolution features has been found.

Assumptions and data uncertainties

There is some evidence of pre-Quaternary hydrothermal systems in older and deeper rocks below the host rock at Yucca Mountain (Bish and Semarge, 1982; Bryant and Vaniman, 1984). The assumption that these systems are no longer active is based on: (1) the intergrowth of younger low-temperature clays over earlier high-temperature clays (Bish and Semarge, 1982), and (2) the lower temperatures (60°C (140°F)) at which these clays now exist in rocks that were hydrothermally altered at high temperatures (180 to 230°C (350 to 450°F)) (Caporuscio et al., 1982). The assumption that solution does not occur in the Topopah Spring Member at Yucca Mountain in low-temperature aqueous systems is supported by the absence of any solution features in drill hole J-13, where the host rock is below the water table (Heiken and Bevier, 1979; Byers and Warren, 1983). Uncertainties in these data are limited to the remote possibility that hydrothermal alteration systems or low-temperature solution zones occur between the present distribution of drill holes and have therefore not been observed. Such sampling uncertainties have not yet been quantified but are expected to be very small.

6.3.1.6.3 Favorable condition

No evidence that the host rock within the site was subject to significant dissolution during the Quaternary Period.

Table 6-32. Summary of analyses for Section 6.3.1.6; dissolution (10 CFR 960.4-2-6)

Condition	Department of Energy (DOE) finding
FAVORABLE CONDITION	
No evidence that the host rock within the site was subject to significant dissolution during the Quaternary Period.	The evidence indicates that this favorable condition is present at Yucca Mountain: no dissolution features have been found or are expected in the potential host rock. Minerals in the host rock are not considered soluble under expected repository conditions.
POTENTIALLY ADVERSE CONDITIONS	
Evidence of significant dissolution within the geologic setting—such as breccia pipes, dissolution cavities, significant volumetric reduction of the host rock or surrounding strata, or any structural collapse—such that a hydraulic interconnection leading to a loss of waste isolation could occur.	The evidence indicates that this potentially adverse condition is not present at Yucca Mountain: no dissolution mechanism is present that could develop hydraulic interconnections that could lead to a loss of waste isolation.
QUALIFYING CONDITION	
The site shall be located such that any subsurface rock dissolution will not be likely to lead to radionuclide releases greater than those allowable under the requirements specified in Section 960.4-1.	The evidence supports the finding that the site meets the qualifying condition and is likely to continue to meet the qualifying condition (level 4): minerals in the host rock are considered insoluble, and dissolution is not a credible process leading to radionuclide releases.

Evaluation

The host rock at Yucca Mountain contains no dissolution fronts or other dissolution features. This is true even to the east of the primary repository area, where the host rock is mostly in the saturated zone (Heiken and Bevier, 1979; Byers and Warren, 1983). None of the reports listed under relevant data in this section cite any evidence of dissolution in the host rock. The mineralogy of the host rock is simple (Bish et al., 1984); more than 98 percent consists of feldspar, quartz, cristobalite, and tridymite; the remainder consists of other silicate and oxide minerals. Under the repository conditions expected at Yucca Mountain, none of these minerals dissolve in water to any meaningful degree.

Conclusion

There is no evidence that the host rock at Yucca Mountain was subject to any dissolution during the Quaternary Period. None of the minerals in the host rock is considered soluble under expected repository conditions. Therefore, the evidence indicates that this favorable condition is present at Yucca Mountain.

6.3.1.6.4 Potentially adverse condition

Evidence of dissolution within the geologic setting--such as breccia pipes, dissolution cavities, significant volumetric reduction of the host rock or surrounding strata, or any structural collapse--such that a hydraulic interconnection leading to a loss of waste isolation could occur.

Evaluation

As stated under the favorable condition, the potential host rock at Yucca Mountain has no dissolution features. This is also true for other rocks at the site, as described in the reports listed under relevant data in this section. While there is some evidence of hydrothermal alteration in the older and deeper rocks below the host rocks (Bish and Semarge, 1982; Bryant and Vaniman, 1984) the evidence indicates that these hydrothermal systems are no longer active and did not result in significant dissolution (Bish and Semarge, 1982; Caporuscio et al., 1982). These deeper zones of pre-Quaternary hydrothermal alteration are dense and nonporous because of secondary mineral precipitation (Caporuscio et al., 1982). The lithophysal cavities that are present in the host rock were formed by the entrapment of gases during the crystallization of the hot volcanic material about 13 million years ago (Byers et al., 1976; Lipman et al., 1966); they are not Quaternary dissolution features. Some lithophysal margins exhibit cross-cutting or overprinted textures that were developed as the lithophysae formed and do not represent Quaternary dissolution fronts (Caporuscio et al., 1982).

Conclusion

At the Yucca Mountain site, there is no evidence of significant dissolution that would provide hydraulic interconnection between the host rock and any immediately surrounding geohydrologic unit. Therefore, the evidence indicates that this potentially adverse condition is not present at Yucca Mountain.

6.3.1.6.5 Disqualifying condition

The site shall be disqualified if it is likely that, during the first 10,000 years after closure, active dissolution, as predicted on the basis of the geologic record, would result in a loss of waste isolation.

Evaluation

The host rock of Yucca Mountain consists of the densely welded and devitrified portion of the unsaturated Topopah Spring Member. About 98 percent of the host rock consists of alkali feldspars, quartz, cristobalite, and tridymite. These minerals are not prone to dissolution in any significant quantities. No evidence of Quaternary dissolution fronts or other Quaternary dissolution features has been found, as discussed under the favorable condition.

Conclusion

On the basis of the geologic record, no dissolution is expected during the first 10,000 years after repository closure, or thereafter. Therefore, the evidence supports a finding that the site is not disqualified on the basis of that evidence and is not likely to be disqualified (level 2).

6.3.1.6.6 Evaluation and conclusion for the qualifying condition on the postclosure dissolution guideline

Evaluation

For all practical purposes the volcanic rocks of Yucca Mountain are not subject to dissolution. The guideline on dissolution applies to soluble rocks (such as salt) that can dissolve at much higher rates than the tuffs of Yucca Mountain. In particular, there is no evidence that the host rock at the site was subject to dissolution during the Quaternary Period, nor is there any reason to suspect that dissolution within the site would provide a hydraulic interconnection between the host rock and the immediately surrounding geohydrologic units. The minerals that compose the rock in and around the site are considered to be insoluble, and no significant dissolution is expected to occur even at the elevated temperatures in the underground repository. Consequently, the formation of active dissolution fronts is not credible for the conditions at Yucca Mountain.

Conclusion

The minerals that compose the rock in and around the Yucca Mountain site are considered insoluble, and significant subsurface rock dissolution is not a credible process leading to radionuclide releases greater than those allowable under the requirements specified in 10 CFR 960.4-1 (1984). Therefore, on the basis of the above evaluation, the evidence supports a finding that the site meets the qualifying condition, and is likely to continue to meet the qualifying condition for postclosure dissolution (level 4).

6.3.1.6.7 Plans for site characterization

Extensive sampling of the proposed horizon is planned during sinking of the exploratory shaft and in situ testing. Other in situ tests will determine the amount of host rock dissolution/precipitation that is possible in the high-temperature zones of the underground facility.

6.3.1.7 Tectonics (10 CFR 960.4-2-7)

6.3.1.7.1 Introduction

The qualifying condition for this guideline is as follows:

The site shall be located in a geologic setting where future tectonic processes or events will not be likely to lead to radionuclide releases greater than those allowable under the requirements specified in Section 960.4-1.

The objective of the postclosure tectonics guideline is to ensure that tectonic processes do not adversely affect the waste-isolation capabilities of a potential repository at the site. This guideline requires that the tectonic history of a site be carefully examined to determine whether the likelihood for future tectonic activity is acceptably small. The tectonic processes that might adversely affect waste isolation after closure are (1) faulting and ground motion, (2) uplift or subsidence, and (3) volcanic activity.

The prediction of future geologic and tectonic processes and corresponding events is uncertain and difficult. The tectonic history of a site, particularly during the Quaternary Period, must be thoroughly examined, and the results of this examination must be used to forecast future tectonic activity and the possible effects of that activity on the isolation capabilities of the site.

The postclosure tectonics guideline consists of one favorable condition, six potentially adverse conditions, one disqualifying condition, and one qualifying condition. The evaluations reported below are summarized in Table 6-33 for all conditions except the disqualifying condition.

Table 6-33. Summary of analyses for Section 6.3.1.7; postclosure tectonics (10 CFR 960.4-2-7)

Condition	Department of Energy (DOE) finding
FAVORABLE CONDITION	
The nature and rates of igneous activity and tectonic processes (such as uplift, subsidence, faulting, or folding), if any, operating within the geologic setting during the Quaternary Period would, if continued into the future, have less than one chance in 10,000 over the first 10,000 years after closure of leading to releases of radionuclides to the accessible environment.	The evidence indicates that this favorable condition is not present at Yucca Mountain: the higher bound on the probability of a basaltic event is estimated at slightly greater than one chance in 10,000 over the next 10,000 years; consequences of other tectonic processes or events are not expected to increase potential for release because low ground-water flux and long travel times are expected to prevent release at the accessible environment for at least 10,000 years following closure.
POTENTIALLY ADVERSE CONDITIONS	
(1) Evidence of active folding, faulting, diapirism, uplift, subsidence, or other tectonic processes or igneous activity within the geologic setting during the Quaternary Period.	The evidence indicates that this potentially adverse condition is present at Yucca Mountain: Quaternary volcanism 230,000 years and older and recurrent Quaternary faulting are found in the vicinity of the site.
(2) Historical earthquakes within the geologic setting of such magnitude and intensity that, if they recurred, could affect waste containment or isolation.	The evidence indicates that this potentially adverse condition is not present at Yucca Mountain: the historical record and geologic evidence indicate no large earthquakes that would be expected to affect containment or isolation if they recurred.
(3) Indications, based on correlations of earthquakes with tectonic processes and features, that either the frequency of occurrence or the magnitude of earthquakes within the geologic setting may increase.	The evidence indicates that this potentially adverse condition is present at Yucca Mountain: future increase in frequency or magnitude of earthquakes at or near Yucca Mountain cannot be ruled out on the basis of available information.

Table 6-33. Summary of analyses for Section 6.3.1.7; postclosure tectonics (10 CFR 960.4-2-7) (continued)

Condition	Department of Energy (DOE) finding
(4) More-frequent occurrences of earthquakes of higher magnitude than are representative of the region in which the geologic setting is located.	The evidence indicates that this potentially adverse condition is not present at Yucca Mountain: the earthquake frequency and magnitude for the geologic setting are the same as or less than the frequency and magnitude of the region.
(5) Potential for natural phenomena such as landslides, subsidence, or volcanic activity of such magnitudes that they could create large-scale surface-water impoundments that could change the regional ground-water flow system.	The evidence indicates that this potentially adverse condition is not present at Yucca Mountain: landslides, subsidence, and volcanic activity are not expected; even if they occurred, they would not be expected to cause surface-water impoundments or change the regional ground-water flow system.
(6) Potential for tectonic deformations--such as uplift, subsidence, folding, or faulting--that could adversely affect the regional ground-water flow system.	The evidence indicates that this potentially adverse condition is not present at Yucca Mountain: large-scale structures control the ground-water system, and tectonic deformations of a magnitude or scale to affect the regional flow system are not expected.
QUALIFYING CONDITION	
The site shall be located in a geologic setting where future tectonic processes or events will not be likely to lead to radionuclide releases greater than those allowable under the requirements specified in Section 960.4-1.	Existing information does not support the finding that the site is not likely to meet the qualifying condition (level 3): potential tectonic events are not likely to cause radionuclide releases greater than allowable; low water flux and travel times greater than 10,000 years in the unsaturated zone are expected to prevent dissolution and transport of radionuclides.

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6.3.1.7.2 Data relevant to the evaluation

Summary of available data

Much of the background data for the tectonic appraisal of the Nevada Test Site area has been developed through many years of surface and subsurface geologic and geophysical studies related to nuclear-weapons testing. The present investigations of Yucca Mountain and its vicinity have built upon this data base by addressing specific subjects, such as faulting (Swadley et al., 1984; Dudley, 1985), regional tectonics (Carr, 1984), stress measurements (Healy et al., 1984), and volcanism (Crowe et al., 1982, 1983; Link et al., 1982). Data are also available on the special techniques used in the evaluation, such as thermoluminescence dating (Wintle and Huntley, 1982). However, much of the published data bearing upon the tectonic stability of the Yucca Mountain region are in the form of progress or preliminary reports, and much work remains to complete the data base. Data are also available on the surficial geology of the site (Scott and Bonk, 1984; Christiansen and Lipman, 1965; Lipman and McKay, 1965) and on ground-water flux rates and chemical and mechanical retardation in the host rock (Wilson, 1985; Sinnock et al., 1984; Travis et al., 1984).

Seismological data of consistent quality have been obtained for only the last few years (Rogers et al., 1983), but two previous reports (Rogers et al., 1976, 1977) provide preliminary data applicable to Yucca Mountain. The historical record of earthquakes within about 10 kilometers (6 miles) of Yucca Mountain has been summarized (USGS, 1984; Rogers, 1986). Seismic data and evaluations for the western United States are also available (Smith, 1978; VanWormer and Ryall, 1980; Thenhaus, 1983; Thenhaus and Wentworth, 1982) and predictions of regional recurrence intervals are taken from Greensfelder et al. (1980) and Ryall and VanWormer (1980). Information about the damage to be expected in underground structures is also available (Pratt et al., 1978, 1979). The acquisition of geodetic data was begun in 1983, but several years of observations will be required before sufficient data are available for analysis.

Workshops were held to review ground motion and related issues for the Yucca Mountain site. A report from these workshops is available (SAIC, 1986).

Assumptions and data uncertainties

The principal assumption is that the geologic history, particularly the history of the Quaternary period (approximately the last 1.8 million years), can be used as the basis for predicting the course of future events. Uncertainties in determining the Quaternary history of the geologic setting of the site arise from the scarcity of precise data on Quaternary deposits and from the difficulty in determining the current tectonic state of this setting with respect to cycles of activity.

6.3.1.7.3 Favorable condition

The nature and rates of igneous activity and tectonic processes (such as uplift, subsidence, faulting, or folding), if any, operating within the geologic setting during the Quaternary Period would, if continued into the future, have less than one chance in 10,000 over the first 10,000 years after closure of leading to releases of radionuclides to the accessible environment.

The conditional probability that a basaltic magmatic intrusion will occur in the future and will intersect a repository at Yucca Mountain during the 10,000 year isolation period is bounded by the range of 4.7×10^{-4} to 3.3×10^{-6} (based on calculations by Crowe et al., 1982). The upper bound probability was calculated on the basis of extremely conservative assumptions, and for this reason, preliminary approximations of mean probability values were calculated from the data presented in Tables IV and V in Crowe et al. (1982), assuming a Gaussian data distribution. The mean probability value calculated on the basis of magma production rate is 7.7×10^{-5} with a standard deviation of 0.11×10^{-5} (Table IV); the mean probability value based on volcanic cone counts is 2.0×10^{-4} with a standard deviation of 1.28×10^{-4} (Table V); and the combined mean using all calculated probability values is 1.3×10^{-4} with a standard deviation 1.33×10^{-4}. Additional investigations are needed to more accurately evaluate the probability of volcanic activity in the Yucca Mountain region.

Probability calculations are not yet available for other tectonic processes. Various investigations are in progress to evaluate more fully the tectonic stability of Yucca Mountain and the surrounding area; they include long-term seismic monitoring, geodetic measurements, and studies of Quaternary faulting and erosion rates. Preliminary studies suggest that the average rate of faulting in the region of Yucca Mountain during the last 2 million years has been less than 0.01 meter (0.03 foot) per 1,000 years (Carr, 1984). Investigations to date covering a 1,100 square-kilometer (425 square-mile) area around the site have found 32 faults that offset or fracture Quaternary deposits. Quaternary faults have been divided into 3 broad age groups as follows: 5 faults last moved between about 270,000 and 40,000 years ago; 4 faults last moved about 1 million years ago; and 23 faults last moved probably between 2 million years and 1.2 million years ago (Swadley et al., 1984). However, work is ongoing to more accurately determine the detailed history of Quaternary fault movement for faults at and near the site. Without this more detailed data, there is uncertainty regarding the expected rate and amount of faulting over the next 10,000 years. Recurrence intervals for earthquakes in the region have been estimated by a number of approaches and are reviewed in the evaluation of the disqualifying condition, Section 6.3.1.7.5. The reported recurrence interval is on the order of 25,000 years for earthquakes of magnitude $M \geq 7$.

Information about the potential effects of earthquakes on underground structures is reviewed in Section 6.3.3.4.5 and indicates that damage in mines is generally less than that at the surface. Damage is not likely to occur unless the mine is very close to the earthquake epicenter. The primary cause of earthquake-induced failure in underground excavations is apparently movement along preexisting faults or collapse at the portal of the tunnel or shaft.

After repository closure, the effect of earthquakes and fault movement on release of radionuclides to the accessible environment is expected to be minimal because very little water is expected to be available to dissolve and transport radionuclides (Wilson, 1985). Using the travel-time estimates from Section 6.3.1.1.5, even if a waste disposal container were breached by fault movement that occurred immediately after closure, no water containing radionuclides could reach the accessible environment for at least 10,000 years and as shown in Section 6.3.1.2.3, chemical and mechanical retardation processes are expected to extend the travel times for radionuclides by at least a factor of 100 (Sinnock et al., 1984; Travis et al., 1984). It is unlikely that seismic activity would cause increases in the flux through the unsaturated zone because flux is controlled by the percentage of precipitation that infiltrates to become percolation. New fractures are unlikely and, if formed, are also unlikely to significantly alter flow conditions because the area is already highly fractured. In addition, care will be taken during waste emplacement to carefully consider the consequences of emplacement in or near recognizable fault zones. It is therefore considered extremely unlikely that faulting could lead to radionuclide releases to the accessible environment over the first 10,000 years after closure.

Conclusion

During the Quaternary Period, various tectonic processes occurred within the geologic setting of Yucca Mountain. The probability of a magmatic intrusion that intersects the repository is on the order of 1 chance in 10,000 over the next 10,000 years. Numerical probabilities are not available for other tectonic processes and events. Low water flux and long travel times should ensure that if radionuclides were released as the result of tectonic activity, they could not reach the accessible environment for at least 10,000 years. Nevertheless, a conservative position is appropriate because of the absence of probability values for most tectonic processes and events and because the upper bound on volcanic event probabilities is larger than the value specified by this condition. Therefore, the evidence indicates that this favorable condition is not present at Yucca Mountain.

6.3.1.7.4 Potentially adverse conditions

(1) Evidence of active folding, faulting, diapirism, uplift, subsidence, or other tectonic processes or igneous activity within the geologic setting during the Quaternary Period.

Evaluation

There is evidence of gentle regional tilting to the southeast of about 4 meters per kilometer (20 feet per mile) during the last few million years (Carr, 1984). At the time of publication of Swadley et al. (1984) there was no unequivocal evidence that surface fault displacement had occurred within a 1,100 square-kilometer (425 square-mile) area around the Yucca Mountain site in the past 40,000 years. However, preliminary dates of a displaced silt horizon obtained by thermoluminescence methods may indicate surface fault displacement on the order of 1 to 10 centimeters in the eastern part of

Crater Flat more recently than about 6,000 years ago (Dudley, 1985). Thermoluminescence is a dating technique that has been used in archaeology, but has not yet been shown to provide reliable dates in geologic applications (Wintle and Huntley, 1982). Ongoing studies to improve the dating of fault displacement in the area will determine the reliability of these preliminary data. A new fault map of the Yucca Mountain site has been prepared by Scott and Bonk (1984) and is shown in Figure 6-20. Continued surface mapping and determination of most recent displacements on faults that are located at and near Yucca Mountain will be an important part of seismic hazard assessment during site characterization. For a more thorough discussion of plans for seismic and tectonic evaluations, see Section 6.3.3.4.5.

Detection of earthquakes in the magnitude (M) ranges M = 4 to 5, M = 5 to 6, M = 6 to 7, and M = 7 to 8 is complete for the most recent 40, 50, 60, and 130 years, respectively, according to USGS (1984). The earthquake record prior to 1978 shows that within about 10 kilometers (6 miles) of Yucca Mountain, 7 earthquakes occurred; 2 had magnitudes of M = 3.6 and M = 3.4; magnitudes were not reported for the remaining 5 earthquakes. They were apparently very small or had magnitudes that could not be determined due to instrument problems. Prior to 1978, standard errors of most locations were ± 7 kilometers (± 4.2 miles) or more (USGS, 1984). A new seismic network has recorded 3 microearthquakes in the same area between August 1978 and the end of 1983; the largest magnitudes (M_L, Richter scale) were approximately M = 2 (Rogers, 1986).

Within the 1,100 square-kilometer (425 square-mile) area around the Yucca Mountain site, 32 faults have been identified as having some evidence of at least a small amount of movement during the Quaternary Period that probably occurred before about 40,000 years ago. Five faults are thought to have last moved between about 270,000 and 40,000 years ago. The remainder of the faults are thought to have last moved between 1 and 2 million years ago (Swadley et al., 1984).

Basaltic eruptions of Late Cenozoic age in the Yucca Mountain area are listed in Table 6-34. Basaltic eruptions occurred periodically in the Crater Flat area west and south of Yucca Mountain during the Quaternary Period (Crowe et al., 1982).

Conclusion

There is evidence of faulting and basaltic volcanism during the Quaternary Period within the geologic setting of Yucca Mountain. There is regional tilting which results in very slow uplift and subsidence. Therefore, the evidence indicates that this potentially adverse condition is present at Yucca Mountain.

(2) Historical earthquakes within the geologic setting of such magnitude and intensity that, if they recurred, could affect waste containment or isolation.

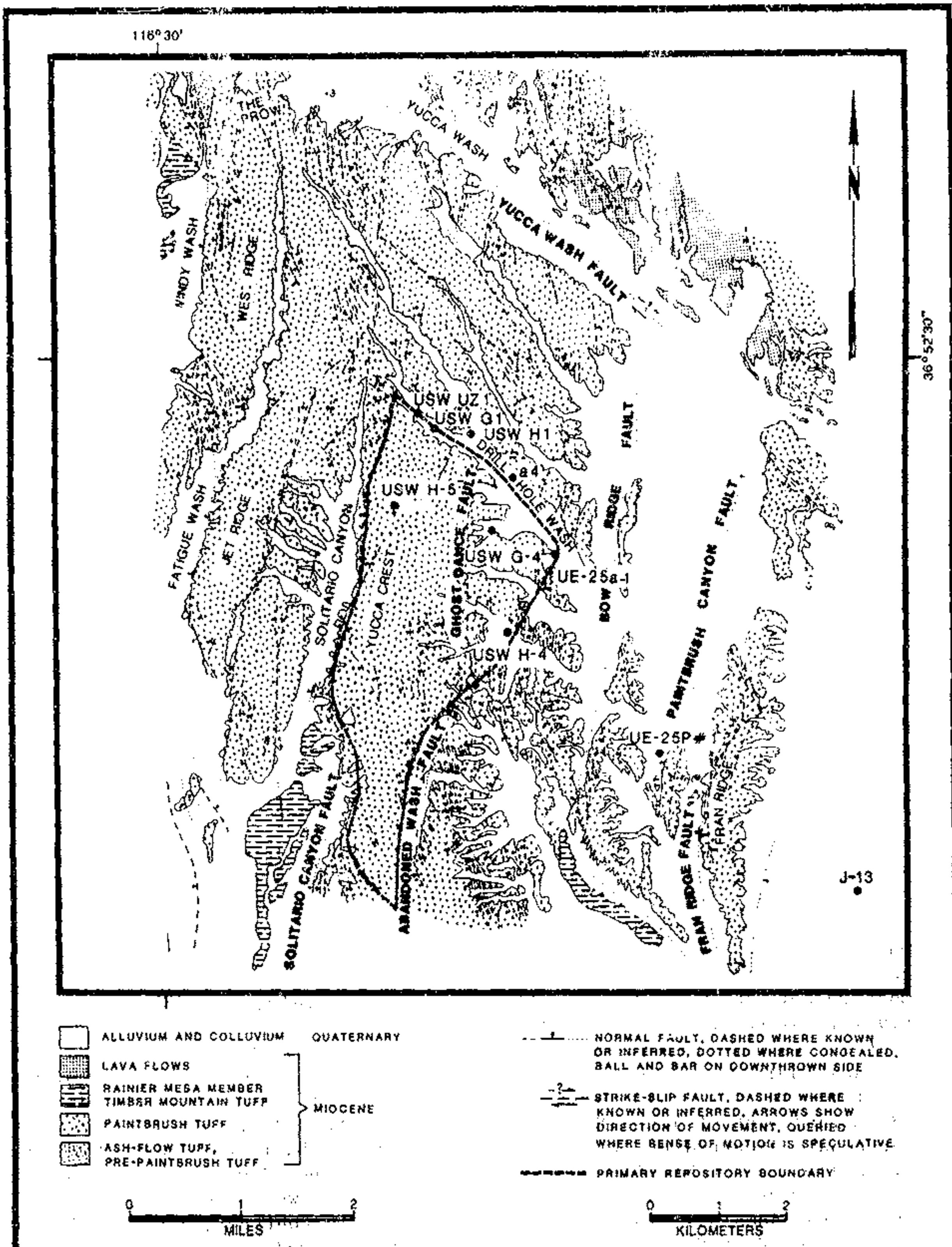

Figure 6-20. Geologic map of Yucca Mountain; primary repository area indicated with dashed line. Modified from Scott and Bonk (1984).

Table 6-34. Potassium-argon ages of late Cenozoic basalts in Yucca Mountain area[a]

	Age (million years)	Mean Age (million years)
Lathrop Wells Volcanic Center	0.29 ± 0.2	
	0.23 ± 0.02	0.27
	0.30 ± 0.10	
Western Rift, Crater Flat	1.14 ± 0.3	
	1.07 ± 0.04	
	1.09 ± 0.3	
	1.07 ± 0.4	1.16
	1.11 ± 0.3	
	1.50 ± 0.1	
Basalt of Sleeping Butte	0.29 ± 0.11	
	0.32 ± 0.15	0.28
	0.24 ± 0.22	
Basalt of Buckboard Mesa	2.82 ± 0.04	2.81
	2.79 ± 0.10	

[a]Data from Crowe et al. (1982).

Evaluation

The peak historical ground acceleration at a location 20 kilometers (12 miles) east of Yucca Mountain is estimated to have been less than 0.1g (Rogers et al., 1977). Pre-1978 historical seismic activity within 10 kilometers (6 miles) of Yucca Mountain shows only 2 earthquakes with Richter magnitudes greater than M = 3. Detection of earthquakes in the magnitude ranges M = 4 to 5, M = 5 to 6, M = 6 to 7, and M = 7 to 8 is complete for the most recent 40, 50, 60, and 130 years, respectively, according to USGS (1984). Although surface faulting has been observed at Pahute Mesa and Yucca Flat in response to nuclear explosions (SAIC, 1986), the closest historical surface faulting accompanying natural earthquakes occurred in 1872 with a magnitude of M = 8+ in Owens Valley, California about 150 kilometers (90 miles) west of Yucca Mountain (Rogers et al., 1977, 1976). This great earthquake occurred on the western margin of the Basin and Range Province, along the Sierra Nevada-Great Basin Boundary Zone (VanWormer and Ryall, 1980), which is a fundamental discontinuity between two contrasting structural domains. The Yucca Mountain area, in contrast, lies on the edge of the East-West Seismic Belt between an area of moderate seismicity on the north, and an area of lower seismicity to the south (see Section 6.3.1.7.5). Two earthquakes with magnitudes of M = 6 have occurred within about 200 kilometers (125 miles) of Yucca Mountain; one occurred in 1908, 110 kilometers

(68 miles) southwest of Yucca Mountain, and one occurred in 1966, about 210 kilometers (130 miles) to the northeast. If the historical earthquakes recurred, they would not be large enough or close enough to Yucca Mountain to have any demonstrable effect on waste containment or isolation (see the qualifying condition evaluation in Section 6.3.1.7.6).

Conclusion

The historical record does not show any earthquakes within the geologic setting of Yucca Mountain that, if they recurred, could adversely affect waste containment or isolation. Furthermore, the historical record discloses no evidence of damaging ground motion or faulting at or near Yucca Mountain. Therefore, the evidence indicates that this potentially adverse condition is not present at Yucca Mountain.

(3) Indications, based on correlations of earthquakes with tectonic processes and features, that either the frequency of occurrence or the magnitude of earthquakes within the geologic setting may increase.

The potential repository site at Yucca Mountain and a large area to the west and south have had a relatively low level of seismicity throughout the historical record (Rogers et al., 1983). The historic earthquake record prior to 1978 shows that within about 10 kilometers (6 miles) of the site, there were 7 earthquakes; 2 had magnitudes of M = 3.6 and M = 3.4; magnitudes were not reported for the remaining 5 earthquakes. They were apparently very small or had magnitudes that could not be estimated due to instrument problems. A new seismic network has recorded 3 minor earthquakes in the same area between August 1978 and the end of 1983; the largest magnitudes (M_L, Richter scale) were approximately M = 2 (USGS, 1984).

Geologic evidence available to date indicates that 32 faults within a 1,100 square-kilometer (425 square-mile) area around the site offset or fracture Quaternary deposits. Five faults are thought to have last moved between about 270,000 and 40,000 years ago. Four faults last moved about 1 million years ago; and 23 faults are thought to have last moved between 2 and 1.2 million years ago (Swadley et al., 1984).

One of the results of ongoing studies is an indication that fault orientation may be more important than evidence of recent movement in determining the potential for renewed activity (Rogers et al., 1983). Microseismic data for Yucca Mountain and a large area to the west and south indicate that faults with strikes from approximately north to northeast appear to be more active than faults of other orientations (Rogers et al., 1983). At present, a preliminary conclusion could be made that the north-trending faults at Yucca Mountain should be considered potentially active even though the absence of fault scarps and the near absence of seismic activity suggest that they are not active (Rogers et al., 1983). It should be noted that the age of most recent surface displacement on a fault does not necessarily correlate with the degree of present seismicity on the fault. This lack of correlation is indicated by the abundant seismicity on fault zones with no record of Quaternary displacement and by the absence of seismicity in some areas of Quaternary faulting (Rogers et al., 1983; USGS, 1984).

From the historical seismicity of the southern Great Basin (two earthquakes of M = 6), and length of active faults, a maximum magnitude of M = 7 to 8 is inferred for earthquakes in the Yucca Mountain region (USGS, 1984). The wide range of focal depths (0 to 10 kilometers (0 to 6 miles)) indicates that some faults in the southern Great Basin extend to considerable depth and thus have large surface areas that would make them capable of producing large earthquakes (USGS, 1984).

The nature of seismic cycles and the relation between the potential for seismicity and the age of most recent movement on faults in the Basin and Range Province are not resolved (see Thenhaus (1983) for a summary of views). Until there is a better understanding of why some areas are stable and other areas are unstable in the same region, it is not possible to rule out future seismic activity on faults at Yucca Mountain (Rogers et al., 1983). This position is taken partly because (1) interpretation of stress measurements at Yucca Mountain could indicate that certain faults may be potentially active (Healy et al., 1984) and (2) faults similar in orientation and style to those at Yucca Mountain exist on Pahute Mesa, where large nuclear tests have resulted in displacement on faults for a distance approaching 10 kilometers (6 miles) in length. Although movement on the faults at Pahute Mesa was induced by nuclear explosions, the extent of faulting, the size of fault displacements, and the magnitude and depths of the accompanying aftershocks indicate that these faults may have been tectonically stressed near the failure point and that slip was triggered by stress changes produced by the explosions (USGS, 1984). It should also be noted that in situ stress measurements alone do not allow quantitative statements about earthquake probability and magnitude (SAIC, 1985b).

Available information is insufficient to determine whether future seismic activity is likely to be more frequent, or of higher magnitude than historic seismicity. In order to provide a consistent interpretation of this potentially adverse condition, the maximum earthquake magnitude in the historical record and the record of Quaternary faulting within the geologic setting are assumed to be the strongest indicators of future earthquake potential for the postclosure time frame. Difficulty in interpreting the Quaternary faulting record leads to the conclusion that the historical record may not reveal the largest earthquake that could occur at Yucca Mountain. Given this interpretation, a conservative position is that the geologic setting of the Yucca Mountain site may experience earthquakes of higher magnitude or frequency than have been historically observed.

Conclusion

The record of Quaternary faulting and the nature of earthquake occurrence in the geologic setting of Yucca Mountain is not understood well enough to permit reliable correlations of earthquakes with tectonic processes and features. In the absence of such correlations, the conservative assumption is that earthquakes larger than those that have historically occurred in the geologic setting of Yucca Mountain may occur in the future. Therefore, the evidence indicates that this potentially adverse condition is present at Yucca Mountain.

(4) More-frequent occurrences of earthquakes or earthquakes of higher magnitude than are representative of the region in which the geologic setting is located.

Evaluation

The Yucca Mountain site is located within the Basin and Range Province and is adjacent to a zone of seismicity considered part of the East-West Seismic Belt in southern Nevada (see Figure 6-21). This belt connects the north-trending Nevada Seismic Belt, about 160 kilometers (100 miles) west of the site, with the north-trending Intermountain Seismic Belt more than 250 kilometers (156 miles) east of the site. Each of these zones of seismicity spans large areas that are heterogeneous in their geologic and seismologic properties (Thenhaus and Wentworth, 1982). There are two earthquakes in the historical record within about 200 kilometers of Yucca Mountain with magnitudes of M = 6; one at Death Valley in 1908, 110 kilometers (68 miles) southwest of the site and the second in 1966, about 210 kilometers (130 miles) to the northeast.

The evaluation of the previous potentially adverse condition reviews the historical record of seismicity for the Yucca Mountain site. The evaluation indicates that it is not possible to rule out future seismic activity on faults at and near Yucca Mountain. However, there is no reason to believe that this seismic activity is likely to be more frequent or of higher magnitude than is typical for the southern Basin and Range Province.

Conclusion

The frequency and magnitude of earthquakes at and near Yucca Mountain during the several years of close monitoring is the same as or less than that for the southern Basin and Range Province. There is no reason to expect that future seismicity at the site is likely to be more frequent or of higher magnitude than is representative of the region in which the geologic setting is located. Therefore, the evidence indicates that this potentially adverse condition is not present at Yucca Mountain.

(5) Potential for natural phenomena such as landslides, subsidence, or volcanic activity of such magnitudes that they could create large-scale surface-water impoundments that could change the regional ground-water flow system.

Evaluation

There is no evidence that subsidence related to dissolution of rocks has occurred, nor are there soluble rocks at the surface or within at least 1,200 meters (3,940 feet) of the surface of Yucca Mountain. Geologic and geomorphic evidence of landslides (Christiansen and Lipman, 1965; Lipman and McKay, 1965; Scott and Bonk, 1984) is limited to relatively small rock slumps along steep erosional slopes of Yucca Mountain. The largest of these slumps is on the northeast side of Yucca Mountain along Yucca Wash, where a set of blocks 500 meters (1,640 feet) wide is slumping into the wash along a complex of 14 minor normal faults that strike parallel to the wash. There is no geomorphic evidence of rapid movement of these blocks, and lateral movement

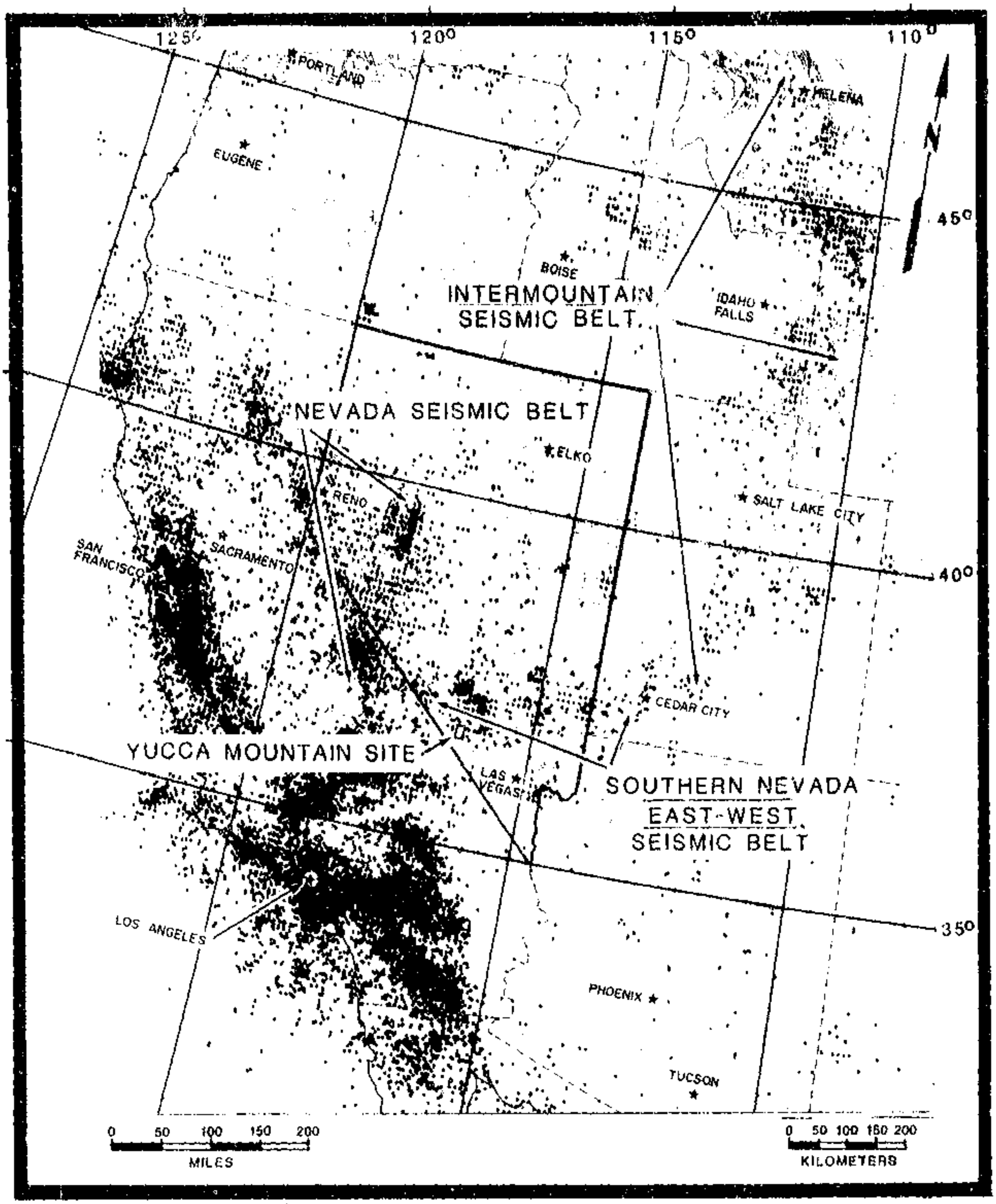

Figure 6-21. Historical seismicity in the western United States showing the Nevada Seismic Belt, the Intermountain Seismic Belt, and the Southern Nevada East-West Seismic Belt. It should be noted that some of the seismicity in the western end of the East-West Seismic Belt represents underground explosions at the Nevada Test Site. For California, the minimum-magnitude earthquakes plotted were Richter M ~ 1; for the rest of the western United States they were Richter M ~ 3. Modified from Smith (1978).

8 0 0 0 8 0 7 9 3

seems to be limited to that observed along normal fault planes that dip 60 to 80°. There is no geomorphic evidence that past slumping of blocks has dammed major drainageways. Furthermore, the slopes do not have a thick cover of soil or colluvial material that could slide down and create dams.

If basaltic eruptions were to occur at or near Yucca Mountain, they might temporarily dam washes. The most recent nearby volcanism occurred at several small basaltic cones that are about 270 thousand to 3.7 million years old and located 8 to 15 kilometers (5 to 9 miles) west and southwest of the site. See Table 6-34 for ages of basalts in the area.

Sites of active basaltic and subordinate silicic volcanism progressively shifted toward the margins of the southwestern Great Basin beginning about 10 million years ago (Crowe et al., 1983), and the likelihood of future eruptions at Yucca Mountain during the time important to waste isolation is small as indicated by the evaluation of favorable condition 1.

Under expected climatic conditions over the next 10,000 years (see Section 6.3.1.4) it is unlikely that sufficient surface runoff could be impounded by any of the above tectonic processes, were they to occur, to change the regional ground-water flow systems.

Conclusion

The creation of large-scale surface-water impoundments by natural phenomena such as landslides, subsidence, or volcanic activity is not likely in the Yucca Mountain area. No effect on the regional ground-water flow system is expected from landslides, subsidence, or volcanic activity. Therefore, the evidence indicates that this potentially adverse condition is not present at Yucca Mountain.

(6) Potential for tectonic deformations--such as uplift, subsidence, folding, or faulting--that could adversely affect the regional ground-water flow system.

Evaluation

Calculations of the amount and the rate of subsidence, uplift, or faulting in the southern Great Basin show that over the last few million years Yucca Mountain and adjacent areas have been relatively stable, particularly in comparison with tectonically active areas, such as Death Valley and Owens Valley (Table 6-35) (Carr, 1984). Folding has not been active in the vicinity of Yucca Mountain for millions of years, although tilting and folding have occurred in the Death Valley region during Pliocene and Quaternary time. Work in progress suggests that gentle warping of Quaternary deposits might have occurred as close to Yucca Mountain as the west side of Crater Flat. An assessment of tectonic warping will be a part of the site characterization process. A level line was run through the Yucca Mountain area in the winter of 1982-1983, and the following winter it was rerun without evidence of change. During November 1985, the line will be upgraded and extended through Mercury, Nevada, to create a level loop originating and terminating at a first-order National Geodetic Survey line.

Table 6-35. Approximate rates of relative vertical tectonic adjustment or burial at selected locations in the southwestern Great Basin during the late Neogene and Quaternary[a]

Location	Rate (meters per 1,000 years or millimeters per year)	Comment
S. Amargosa Desert Valley	<0.01	Based on a 3-million-year old ash bed in lake deposits about 5 meters below the surface.
Crater Flat, central	<0.01	Basalt dated by potassium-argon method at 1.2 million years is at the present surface and has not been deformed or subsided into the basin.
Crater Flat, eastern	<0.01	Based on an offset in alluvium (allowing for 0.6 meter of erosion) of 3.0 meters in 1.1 million years.
Crater Flat, southeastern	<0.02	Offset of alluvium in a minimum time of 40,000 years. Actual time was probably closer to 260,000 years.
Crater Flat, USW VH-2 drill hole	0.03	Burial of basalt about 11 million years old.
Yucca Mountain	0.03	Based on maximum of 460 meters of offset of Tiva Canyon Member in last 12.8 million years. For the Quaternary, a very conservative estimate is <0.01 meters per 1,000 years, based on maximum credible amount of displacement (10 meters) in Quaternary time.
N. W. Frenchman Flat	0.06[b]	Burial of 3-million-year old ash bed at depth of 195 meters; not in most active part of the Frenchman Flat Basin.
S. Yucca Flat	0.16[b]	Based on amount of displacement of an 8.1-million-year old basalt in drill holes.
Searles Valley	0.22[b]	Burial of 3-million-year old ash bed in core at depth of 691 meters.

Table 6-35. Approximate rates of relative vertical tectonic adjustment or burial at selected locations in the southwestern Great Basin during the late Neogene and Quaternary[a] (continued)

Location	Rate (meters per 1,000 years or millimeters per year)	Comment
Death Valley, foot of Black Mountains	0.3	Based on estimated displacement of Artist's Drive Formation of 1,525 meters in 5 million years.
Sierra Nevada-Owens Valley-White-Inyo Mountains	0.4	Average of 9 estimates (range 0.2-1.0 meters per 1,000 years).
Coso Range-Rose Valley	1.8	Offset of 2.5 million-year-old lava flow.

[a]Data from Carr (1984).
[b]Maximum rate.

The available data on several specific faults in the Yucca Mountain area seem to show generally decreasing rates and amounts of offset through about the last 10 million years (Carr, 1984). The data for older faulting are obtained at locations where the offset of several volcanic units of known ages can be determined. Control for dating events of the last 8 million years depends mainly on understanding and dating alluvial-stratigraphic units that have limited vertical exposures. The absolute ages of some of these units are not well known at present. Approximately 180 scarps or lineaments that are presumed to be fault related have been identified within 100 kilometers (62 miles) of Yucca Mountain (Carr, 1984). About one-fourth of these are linear or curvilinear mountain fronts; the remaining 135 are actual fault scarps or lineaments in the alluvium. Most of the alluvial scarps are low and subdued by erosion. Ages of movement on faults that offset Quaternary deposits are reviewed in the above evaluation of potentially adverse condition 3.

The rates of uplift, subsidence, or faulting in the past have been very low; it is postulated that similar rates will prevail in the future. If the rates of uplift, subsidence, or faulting in a portion of the ground-water system were significantly changed relative to those of other portions of the system, the ground-water flow path between the repository and the accessible environment could be affected. Ground-water flow could be either retarded or accelerated. However, the scale of the effects on ground-water flow are expected to be small because the present ground-water system is controlled by large regional structures that probably could not be altered significantly by tectonic events during the time period important to waste isolation.

Conclusion

The Yucca Mountain site has a very small potential for tectonic deformations like uplift, subsidence, folding, or faulting of a magnitude or scale that would affect regional ground-water flow. The regional ground-water system is controlled by geologic structures of such complexity and scale that it could not be significantly modified over short time periods by any expected tectonic event. Therefore, the evidence indicates that this potentially adverse condition is not present at Yucca Mountain.

6.3.1.7.5 Disqualifying condition

> A site shall be disqualified if, based on the geologic record during the Quaternary Period, the nature and rates of fault movement or other ground motion are expected to be such that a loss of waste isolation is likely to occur.

Evaluation

The potential repository site at Yucca Mountain and a large area to the west and south have had a relatively low level of seismicity throughout the historical record (Rogers et al., 1983). The historic earthquake record prior to 1978 shows that within about 10 kilometers (6 miles) of the site, there were 7 earthquakes; 2 had magnitudes of M = 3.6 and M = 3.4; magnitudes for the remaining 5 were not reported. They were apparently very small or had magnitudes that could not be estimated due to instrument problems. A new seismic network has recorded 3 minor earthquakes in the same area between August 1978 and the end of 1983; the largest magnitudes (M_L, Richter scale) were approximately M = 2 (Rogers, 1986). Within about 200 kilometers (124 miles) of Yucca Mountain, there have been two historical earthquakes with Richter magnitudes of M = 6. One earthquake occurred in 1908 at Death Valley about 110 kilometers (68 miles) southwest of Yucca Mountain, and the other occurred in 1966, about 210 kilometers (130 miles) northeast of the site. The Owens Valley, California, earthquake of 1872, which is estimated to have had a magnitude of M = 8+ on the Richter scale, represents the closest historical surface faulting. It was located about 150 kilometers (90 miles) west of the site in a different seismic zone (see Section 6.3.1.7.4, potentially adverse condition 2).

Geologic evidence available to date indicates that 32 faults within a 1,100 square-kilometer (425 square-mile) area around the site offset or fracture Quaternary deposits. Five faults are thought to have last moved between about 270,000 and 40,000 years ago. The remainder of the faults are thought to have last moved between 1 and 2 million years ago (Swadley et al., 1984). At the time of publication of Swadley et al. (1984) there was no unequivocal evidence that surface fault displacement had occurred within a 1,100 square-kilometer (425 square-mile) area around the Yucca Mountain site in the past 40,000 years. However, preliminary dates of a displaced silt horizon obtained by thermoluminescence methods may indicate surface fault displacement on the order of 1 to 10 centimeters in the eastern part of Crater Flat more recently than about 6,000 years ago (Dudley, 1985). Thermoluminescence is a dating technique that has been used in archaeology, but has not yet been shown to provide reliable dates in geologic applications (Wintle and Huntley, 1982). Ongoing studies to improve the dating of fault displacement in the area will determine the reliability of these preliminary data.

Deformation rates at Yucca Mountain during the last approximately 10 million years have been about 4 times less than those in adjacent parts of the Basin and Range Province. Preliminary estimates suggest that a rate of 0.01 meter (0.03 foot) per 1,000 years is a realistic maximum for fault displacement in the Quaternary Period at Yucca Mountain (Carr, 1984).

A number of different approaches have been used to estimate recurrence intervals for earthquakes in the region. Rerupture times (recurrence intervals) estimated for various portions of the Basin and Range Province are assembled from the literature in Table 6-36. The estimates range from 25,000 years for $M \geq 7$, 2,500 years for $M \geq 6$, and 250 years for $M \geq 5$. Recurrence intervals shown in Table 6-36 demonstrate the variability in estimates, resulting from possible real differences for differing regions. The table shows that recurrence intervals for $M \geq 7$ earthquakes for the region south and east of Yucca Mountain are longer than those for the Nevada Test Site (NTS) region by about a factor of 7. At this time, recurrence estimates can only provide insight regarding possible recurrence intervals for faults near Yucca Mountain. Until detailed fault studies are fully completed, there is large uncertainty regarding the appropriate recurrence intervals for these faults. However, the available data (Swadley et al., 1984; Dudley, 1985; and USGS, 1984), furnish no evidence to suggest that the recurrence interval would be shorter than on the order of 25,000 years for major ($M \geq 7$) earthquakes. It should also be noted that there is no information currently available on the seismogenic potential of faults at or near Yucca Mountain, so that the occurrence of a magnitude 7 earthquake in the area can neither be anticipated nor can it be ruled out.

As noted above, the NTS region occupies an intermediate position between a large area of higher estimated seismicity to the north and an area of lower seismicity in the Las Vegas region to the south (see Figure 6-22). Except for a cluster of seismicity due to the water load of Lake Mead, Figure 6-22 shows a fan-shaped region extending southeast from the repository site that is virtually free of earthquakes of $M = 4$ or larger. USGS (1984) calls attention to the near absence of seismicity at approximately the $M > 4$ level in some parts of a 100-kilometer (60-mile) radius surrounding the site.

Rogers et al. (1983) and USGS (1984) conclude that the seismic evidence suggests that faults of north to northeast trend are most susceptible to slip in the current stress field, citing evidence from stress measurements at Yucca Mountain (Healy et al., 1984) and from faults of similar orientations at Pahute Mesa, where fault movements have been induced by nuclear explosions. For purposes of a preliminary evaluation, the seismic hazard for Yucca Mountain was estimated under the assumption that Yucca Mountain faults were not active. The most likely peak deterministic ground acceleration at Yucca Mountain was estimated to be 0.4g. This acceleration would result from a full-length fault rupture (length 17 kilometers (10 miles), magnitude 6.8)

Table 6-36. Rerupture times for faults in the southern Basin and Range Province

Reference	Area	Rerupture time for M $\geq$ 7.0 unless otherwise noted (years)	Comments
Ryall and VanWormer (1980)	Western Great Basin[a]	7,000-10,000[b]	From instrumental data for 1932-1969 and 1970-1974
Greensfelder et al. (1980)	East-West Seismic Belt, including Nevada Test Site[c]	25,000	Logarithmic mean of two data sets
		2,500[d]	For earthquakes with M $\geq$ 6
		250[d]	For earthquakes with M $\geq$ 5
	Las Vegas Region[e]	190,000	Logarithmic mean of two sets

[a]Entire 225,000-square-kilometer region containing Holocene scarps.
[b]Values were calculated on the assumption that a typical rupture zone has an area of 1,000 square kilometers, and that such rupture zones are contained within the subject region.
[c]Basin and Range Seismotectonic Subprovince 4 of Greensfelder et al. (1980), a 34,000-square-kilometer area containing the Nevada Test Site. (Log N = 2.60 - 1.0 M, where N = number of earthquakes of magnitude greater than or equal to M.)
[d]Recurrence interval estimates based on data in Greensfelder et al. (1980).
[e]Basin and Range Seismotectonic Subprovince 5 of Greensfelder et al. (1980), a 73,000-square-kilometer area of very low seismicity north of 34°N. (Log N = 1.72 - 1.0 M, where N = number of earthquakes of magnitude greater than or equal to M.)

on the Bare Mountain Fault, which is 14 kilometers (9 miles) west of the site. The probabilistic results discussed by Rogers et al. (1977) and USGS (1984) demonstrate that uncertainties exist in the evaluation of seismic hazard. Different assumptions regarding the appropriate recurrence model, attenuation relationships, and the identification of specific faults as seismic sources can result in widely different estimates of acceleration for a given probability. At this time, it is premature to place much confidence

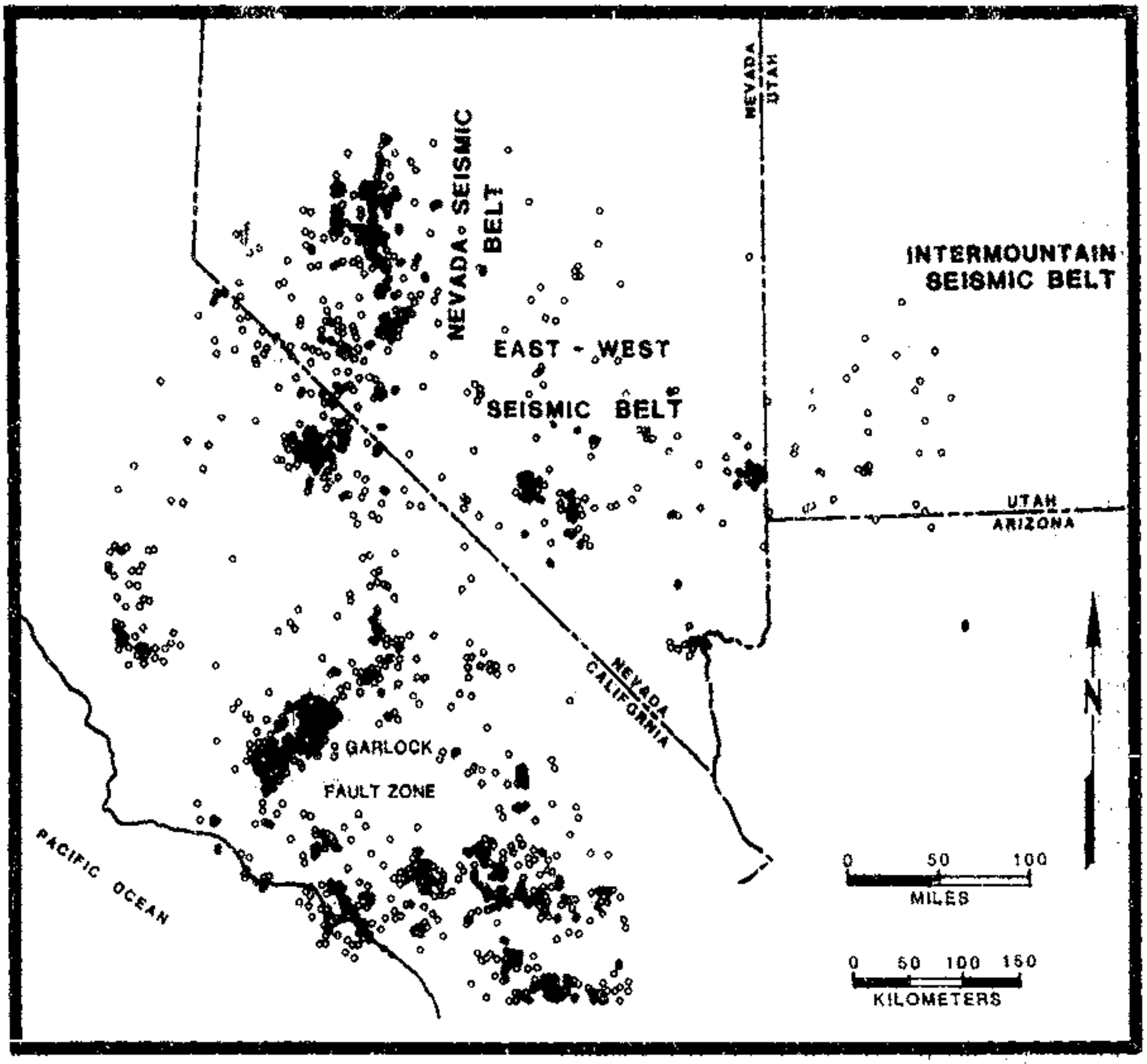

Figure 6-22. Historic earthquakes of Mercalli intensity ≥ V or magnitude ≥ 4.0 within 500 kilometers (311 miles) of the Yucca Mountain site through 1974. Those circles that appear solid indicate multiple events. Modified from USGS (1984).

in these estimates, other than to use them to provide insight, until a more complete assessment can be made of the various input parameters into a probabilistic seismic hazard analysis. During site characterization, the seismogenic potential of faults at and near Yucca Mountain will be evaluated to determine the most probable earthquake and faulting scenarios that will need to be considered for evaluation of postclosure repository performance. Further discussion of the approach to be taken for these investigations is presented in Section 6.3.3.4.5.

The ground motion or faulting that is possible at the Yucca Mountain site is likely to have little effect on waste isolation. It is known that earthquake damage to underground facilities is generally much smaller than surface damage (Pratt et al., 1978, 1979). On the basis of detailed surface mapping, faults that cut the potential repository host rock are expected to have easily recognizable displacement if they are large enough to be of concern. Care will be taken during repository development to avoid recognizable faults that appear to have any possibility of renewed activity. Formation of new faults, although not likely, could affect the durability of the containers during the containment period, with the most serious consequence being container rupture. However, in order for radionuclides to be dissolved from the waste and transported from the repository a sufficient quantity of water must be available. The expected very low flux (less than 0.5 millimeter (0.02 inch) per year) at Yucca Mountain (Wilson, 1985) has been shown to be insufficient to transport radionucides in quantities that could exceed release limits to the accessible environment (Section 6.4.2). Furthermore, calculations by Sinnock et al. (1984) show that the U.S. Environmental Protection Agency (EPA) limits on cumulative curies released to the accessible environment are not violated for waste package containment times as short as 300 years and fluxes that are 40 times the upper bound of 0.5 millimeter (0.02 inch) per year. Flux limitations and long travel times of more than 10,000 years (see Section 6.3.1.1.5), provide confidence that an earthquake- or fault-induced disruption of the repository would be extremely unlikely to cause radionuclide releases to the accessible environment in excess of those allowable under 40 CFR Part 191 (1985).

Conclusion

The geologic record of faulting during the Quaternary Period suggests that the Yucca Mountain site could experience seismicity and faulting in the future. There is, however, no clear evidence that a major earthquake is likely to occur at or near Yucca Mountain. In addition, the consequence of fault movement on waste isolation in this geologic setting is expected to be minimal. The very low water flux that is available for radionuclide transport ensures that EPA release limits are not likely to be exceeded. Confidence in this prediction is enhanced by conservative calculations showing that ground-water travel times exceed 10,000 years. Therefore, the evidence does not support a finding that the Yucca Mountain site is disqualified (level 1).

6.3.1.7.6 Evaluation and conclusion for the qualifying condition on the postclosure tectonics guideline

The available data and interpretations indicate that silicic volcanism ceased at least 8 million years ago in the southern Great Basin. Basaltic volcanic activity has continued during the last 6 to 8 million years, but in episodes that are separated by millions of years to hundreds of thousands of years (Crowe et al., 1982). The most recent episode of basaltic activity near Yucca Mountain occurred approximately 270,000 years ago. The rates of vertical tectonic adjustments during the last 5 million years, as evidenced by displaced rock units of Pliocene and Quaternary age, have been much lower than those of older episodes (Carr, 1984). As displayed in Table 6-36, recurrence intervals for major earthquakes ($M \geq 7$) in the region have been estimated to be on the order of 25,000 years. Recurrence intervals for $M \geq 6$ earthquakes are reported to be on the order of 2,500 years, and $M \geq 5$ earthquakes have recurrence intervals on the order of 250 years.

Future tectonic events, including volcanism and faulting, are unlikely to lead to loss of waste containment or isolation. The probability that basaltic volcanism will disrupt the Yucca Mountain site over a 10,000-year period is estimated to be about 1 chance in 10,000 (based on data from Crowe et al., 1982). The consequences of this basaltic event were assessed by Link et al. (1982). They estimated the expected radionuclide release over a 10,000 year period, assuming that volcanism occurs between 100 and 10,000 years, to be 1.8 curies or 0.038 curies per 1,000 metric tons of heavy metal (MTHM) for a spent fuel repository. Because the probability of this event is estimated to be less than 0.1 over the 10,000-year period, the U.S. Environmental Protection Agency (EPA) release limits should be multiplied by ten according to 40 CFR 191, Subpart B (1985). The isotopes with the largest expected releases under this scenario, relative to their respective EPA release limits, are plutonium-239 and -240. Both are limited by the EPA to cumulative releases over 10,000 years of 100 curies per 1,000 MTHM, or 1,000 curies per 1,000 MTHM for unlikely events. Expected release under the volcanism scenario for each of these isotopes is 23 curies per 1,000 MTHM. All other isotopes are released in quantities that are much smaller relative to the EPA limits.

It is also unlikely that faulting and strong ground motion could cause loss of containment or isolation. Fault displacement could rupture waste disposal containers intercepted by the fault; however, care will be taken during repository development to avoid recognizable faults that appear to have any possibility of renewed activity. Discussions in the previous section indicate that earthquakes associated with large displacements are likely to occur on prominent fault zones that have already been recognized; an avoidance strategy is therefore plausible during container emplacement. In addition, the unsaturated conditions at Yucca Mountain limit the water available to dissolve and transport radionuclides so much that the potential for loss of isolation is very small. Another concern is the ground motion resulting from a nearby earthquake. This motion is unlikely to be severe enough at depth to cause container rupture, as indicated in the discussion in the preclosure disqualifying condition (Section 6.3.3.4.5). Strength requirements that will be imposed on the containers during surface handling will require that containers be able to withstand impact velocities during drop tests that are much more severe than are likely to be experienced after emplacement in the repository. Furthermore, studies by Sinnock et al. (1984) have shown that EPA limits on cumulative curies released to the accessible environment are not violated for waste package containment times as short as 300 years and fluxes that are 40 times the upper bound of 0.5 millimeter (0.02 inch) per year (see Section 6.3.1.1 for calculation of ground-water travel times to the accessible environment and Section 6.4.2 for estimates of releases of radionuclides to the accessible environment).

At this time, no plausible scenarios have been developed that suggest earthquakes, faulting, or volcanic activity is likely to lead to unacceptable releases of radionuclides.

Conclusion

On the basis of presently available data and interpretations for the Yucca Mountain site, the rates and magnitudes of tectonic processes during the Quaternary Period were relatively low. No mechanisms have been identified whereby the expected tectonic processes or events could lead to unacceptable radionuclide releases. Therefore, on the basis of the above evaluation, the evidence does not support a finding that the site is not likely to meet the qualifying condition for postclosure tectonics (level 3).

6.3.1.7.7 Plans for site characterization

During site characterization, field investigations will continue to evaluate the tectonic activity of the Yucca Mountain site and surrounding region. These investigations will include (1) more trenching, including trenching parallel to scarps as well as across scarps, to evaluate possible strike-slip motion, (1a) search for obscure fault scarps with low sun-angle aerial photography, (1b) more detailed geomorphic studies of the faults using state-of-the-art structural geomorphology techniques; (2) monitoring of earthquake activity at the site and in the surrounding region; (3) monitoring of ground motion in drill holes; (4) precise monitoring of geodetic positions and elevations; (5) more studies of geomorphic history during the Quaternary Period; (6) additional measurements of in situ stress in drill holes and underground workings; (7) compilation of various types of structural syntheses of the geology of the Nevada Test Site (NTS) region; (8) compilation of combined geologic maps of Yucca Mountain showing detailed Quaternary fault distribution together with detailed distribution of Quaternary stratigrahic units; (9) compilation of earthquake epicentral plots by fractional magnitude intervals to evaluate conceptual models of the seismic quiet zone southeast of the NTS. In addition, more data on the geohydrologic system will be obtained, which will enable the local ground-water system to be modeled in detail. This modeling will then permit the effects of credible tectonic events on ground-water flow and radionuclide transport to be described.

6.3.1.8 Human interference technical guideline (10 CFR 960.4-2-8): Natural resources (10 CFR 960.4-2-8-1) and site ownership and control (10 CFR 960.4-2-8-2)

6.3.1.8.1 Introduction

This guideline contains two qualifying conditions. One is for the natural resources guideline, and one is for the postclosure site ownership and control guideline. The postclosure site ownership and control guideline is discussed in Section 6.2.1.1.

The qualifying condition for this guideline is as follows:

The site shall be located such that--considering permanent markers and records and reasonable projections of value, scarcity, and technology--the natural resources, including ground water suitable for crop irrigation or human consumption without treatment, present at or near the site will not be likely to give rise to interference activities that would lead to radionuclide releases greater than those allowable under the requirements specified in Section 960.4-1.

The human interference technical guideline consists of the natural resources and postclosure site ownership and control technical guidelines. The guideline on natural resources addresses general concerns about surface and subsurface resources, including minerals, energy resources, and ground water. It considers these resources with respect to reducing or removing the incentives for economically motivated postclosure human-interference activities that could adversely affect the isolation capabilities of a site. The guideline on site ownership addresses the requirements of the Nuclear Regulatory Commission for the U.S. Department of Energy to obtain ownership and surface and subsurface rights to land and minerals within the controlled area of the repository. This section evaluates the Yucca Mountain site against the overall qualifying condition for human interference and against the conditions of the natural resources guideline. Section 6.2.1.1 provides relevant data and the evaluation with respect to the site ownership and control guideline.

The natural resources guideline contains two favorable conditions, five potentially adverse conditions, two disqualifying conditions, and one qualifying condition. The site ownership and control guideline contains one favorable condition, one potentially adverse condition, and one qualifying condition. Table 6-37 summarizes the evaluations for the natural resources guideline, except the disqualifying conditions. See Section 6.2.1.1 for the summary table for site ownership and control.

6.3.1.8.2 Data relevant to the evaluation

The energy- and mineral-resource potential of Yucca Mountain and surrounding areas has been evaluated by Bell and Larson (1982) and by Quade and Tingley (1983). Boreholes have been drilled in and around Yucca Mountain for the Nevada Nuclear Waste Storage Investigations Project (Maldonado and Koether, 1983; Spengler et al., 1981; Scott and Castellanos, 1984), and core samples and drill cuttings have been routinely analyzed by geochemical

Table 6-37. Summary of analyses for Section 6.3.1.8; human interference technical guideline (10 CFR 960.4-2-8): natural resources (10 CFR 960.4-2-8-1) and site ownership and control (10 CFR 960.4-2-8-2) (see Table 6-2)

Condition	Department of Energy (DOE) finding
FAVORABLE CONDITIONS	
(1) No known natural resources that have, or are projected to have in the foreseeable future, a value great enough to be considered a commercially extractable resource.	The evidence indicates that this favorable condition is present at Yucca Mountain: no present or projected uranium, hydrocarbon, or critical mineral resources have been identified; potential development of ground water for irrigation is not expected because of unsuitable topography and great depth of water table.
(2) Ground water with 10,000 parts per million or more of total dissolved solids along any path of likely radionuclide travel from the host rock to the accessible environment.	The evidence indicates that this favorable condition is not present at Yucca Mountain: ground water has total dissolved solids less than 300 parts per million.
POTENTIALLY ADVERSE CONDITIONS	
(1) Indications that the site contains naturally occurring materials, whether or not actually identified in such form that (i) economic extraction is potentially feasible during the foreseeable future or (ii) such materials have a greater gross value, net value, or commercial potential than the average for other areas of similar size that are representative of, and located in, the geologic setting.	The evidence indicates that this potentially adverse condition is not present at Yucca Mountain: no critical or unique energy, metallic, or nonmetallic resources have been identified in the site vicinity. There is no credible potential for the use of water resources for agriculture.

Table 6-37. Summary of analyses for Section 6.3.1.8; human interference technical guideline (10 CFR 960.4-2-8): natural resources (10 CFR 960.4-2-8-1) and site ownership and control (10 CFR 960.4-2-8-2) (see Table 6-2) (continued)

Condition	Department of Energy (DOE) finding
(2) Evidence of subsurface mining or extraction for resources within the site if it could affect waste containment or isolation.	The evidence indicates that this potentially adverse condition is not present at Yucca Mountain: no evidence of subsurface mining or extraction for resources has been found at the site.
(3) Evidence of drilling within the site for any purpose other than repository-site characterization to a depth sufficient to affect waste containment and isolation.	The evidence indicates that this potentially adverse condition is not present at Yucca Mountain: there has been no drilling at the site except for evaluation for the potential repository.
(4) Evidence of a significant concentration of any naturally occurring material that is not widely available from other sources.	The evidence indicates that this potentially adverse condition is not present at Yucca Mountain: resources in the site vicinity are also found outside the vicinity where they are more abundant and can be extracted more economically.
(5) Potential for foreseeable human activities--such as ground-water withdrawal, extensive irrigation, subsurface injection of fluids, underground pumped storage, military activities, or the construction of large-scale surface-water impoundments--that could adversely change portions of the ground-water flow system important to waste isolation.	The evidence indicates that this potentially adverse condition is not present at Yucca Mountain: groundwater development for irrigation is not expected because of unsuitable topography and great depth to the water table. If extensive withdrawal of ground water lowered the water table, improved waste isolation would result because of increases in unsaturated zone travel times. Limited energy and mineral resources limit the potential for human activities.

Table 6-37. Summary of analyses for Section 6.3.1.8; human interference technical guideline (10 CFR 960.4-2-8): natural resources (10 CFR 960.4-2-8-1) and site ownership and control (10 CFR 960.4-2-8-2) (see Table 6-2) (continued)

Condition	Department of Energy (DOE) finding
	QUALIFYING CONDITION
<u>Human interference: natural resources</u>	
The site shall be located such that--considering permanent markers and records and reasonable projections, of value, scarcity, and technology--the natural resources, including ground water suitable for crop irrigation or human consumption without treatment, present at or near the site will not be likely to give rise to interference activities that would lead to radionuclide releases greater than those allowable under the requirements specified in Section 960.4-1.	Available evidence does not support the finding that the site is not likely to meet the qualifying condition (level 3): no known valuable natural resources are present, and potential for future natural resources is low; permanent markers are expected to remain effective and discourage future human interference.
<u>Human interference: site ownership and control</u>	
See Table 6-2 for second human interference qualifying condition which is the qualifying condition for postclosure site ownership and control.	

8 0 0 0 8 0 8 0 7

methods. Field exploration and geologic mapping have been conducted by the U.S. Geological Survey (Christiansen and Lipman, 1965; Lipman and McKay, 1965; Scott and Bonk, 1984). Archaeological surveys have been conducted in the site area to detect historical evidence of resource extraction activities (Pippin et al., 1982; Pippin, 1984).

Geothermal resources in the area were inventoried by Garside and Schilling (1979), and evaluated by Trexler et al. (1979). The hot springs studied are northwest and south of the Yucca Mountain site. Data from the site-specific investigations were compared to the general requirements in White (1973) in order to determine geothermal resource potential. Detailed discussions of the potential for energy and mineral resources, including assumptions and data uncertainties, are presented in Section 3.2.4.

A ground-water resource potential map has been prepared by Sinnock and Fernandez (1982). Data on water quality in the site vicinity have been obtained by Benson et al. (1983) and Winograd and Thordarson (1975). The regional ground-water flow model for the site is discussed in Section 3.3.2, which also includes discussions of ongoing work.

6.3.1.8.3 Favorable conditions

(1) No known natural resources that have or are projected to have in the foreseeable future a value great enough to be considered a commercially extractable resource.

Evaluation

Present knowledge of the status of energy resources at or near the site suggests that (1) there is no potential for any commercially attractive geothermal or hydrocarbon resources at or near Yucca Mountain and (2) there is no indication of uranium resources at Yucca Mountain. The energy resources appraised by Bell and Larson (1982) include hydrocarbons (e.g., oil, gas, oil shale, and coal); low- to moderate-temperature sources of geothermal energy; and radioactive minerals (i.e., uranium and thorium). None of the project boreholes have shown evidence of the presence of energy or mineral resources (Maldonado and Koether, 1983; Spengler et al., 1981; Scott and Castellanos, 1983). The area around Yucca Mountain is extremely well known in terms of heat flow. Hot springs and wells were inventoried and evaluated by Garside and Schilling (1979) and Trexler et al. (1979). Data from more than 60 wells (some as deep as 1,800 meters (6,000 feet)) is available, and water temperatures range from 21 to 65°C (70 to 149°F). With present technology, this temperature range is insufficient for commercial power generation, which requires temperatures of at least 180°C (350°F) (White, 1973). Specific mineral resources appraised include base and precious metals (e.g., silver), as well as significant industrial minerals and rock materials (e.g., gravel). Detailed information supporting this evaluation is presented in Section 3.2.4, and a resource map is shown in Figure 6-23.

Although ground water is used for irrigation in Ash Meadows and in the Amargosa Valley, it is unlikely to be used for irrigation at Yucca Mountain because of the rugged terrain and great depth to the water table (Sinnock and Fernandez, 1982). Supporting data for this evaluation are given in

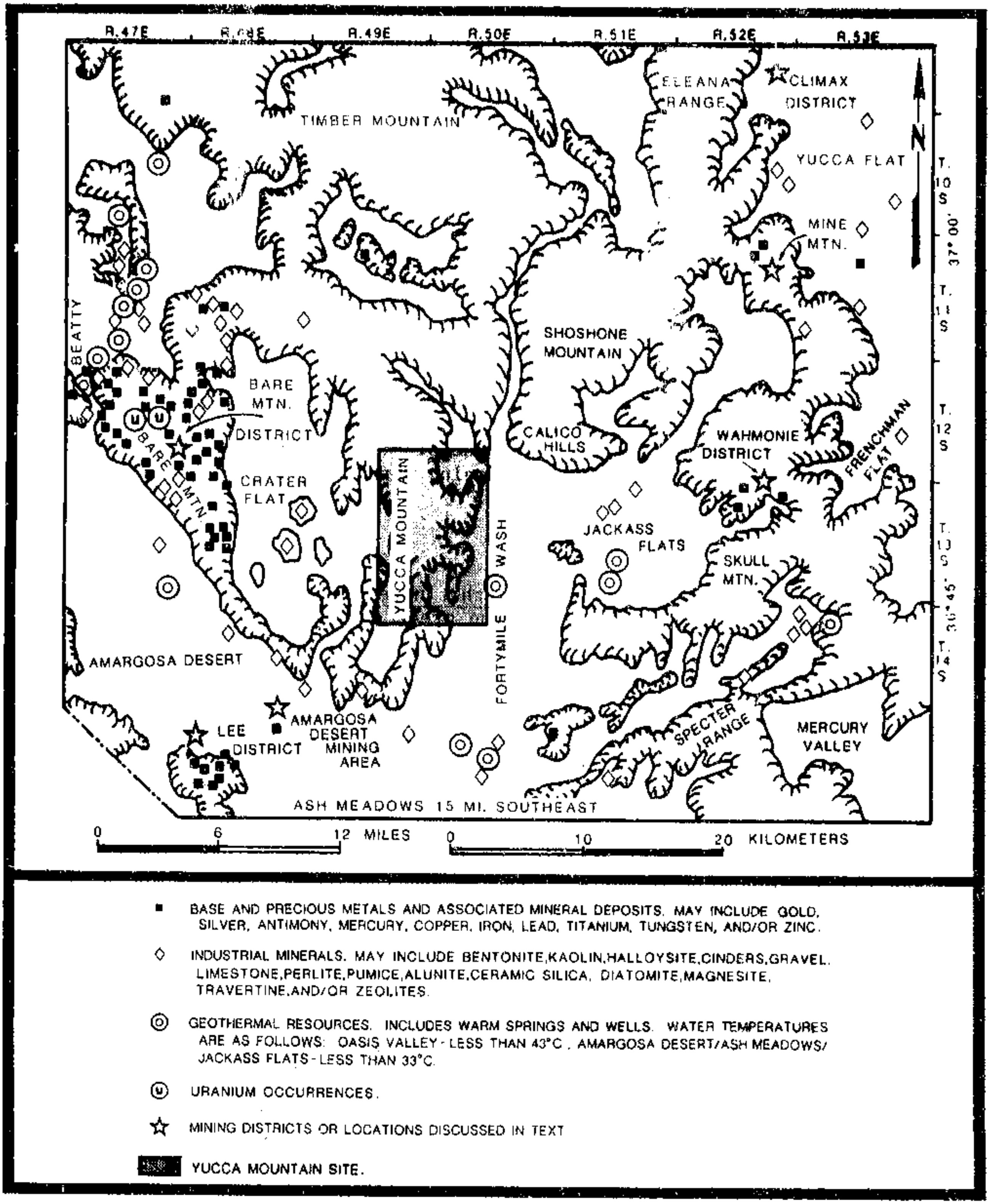

Figure 6-23. Location of metallic ore deposits, industrial minerals, thermal waters, and mining districts in the vicinity of Yucca Mountain. Modified from Bell and Larson (1982) and Trexler et al. (1979).

Section 3.6.3.3, which discusses the uses and sources of water in the Amargosa Desert. Other pertinent information can be found in the hydrology (Section 6.3.3.3) and socioeconomics (Section 6.2.1.7) guidelines.

Conclusion

There are no known natural resources that have, or are projected to have in the foreseeable future, a value great enough to be considered commercially extractable. Therefore, the evidence indicates that this favorable condition is present at Yucca Mountain.

(2) Ground water with 10,000 parts per million or more of total dissolved solids along any path of likely radionuclide travel from the host rock to the accessible environment.

Evaluation

Most samples of ground water obtained to date from wells and springs throughout the region, including the Yucca Mountain area, have total-dissolved-solids (TDS) concentrations of less than 300 parts per million (Benson et al., 1983). Winograd and Thordarson (1975) report a TDS value of 886 parts per million for Well J-11 in Jackass Flats. Thus, ground water with 10,000 parts per million or more of total dissolved solids probably does not occur along any flow path.

Conclusion

Reported analyses of local ground water indicate that it is unlikely that the total dissolved solids could reach or exceed 10,000 parts per million in the ground water along any path of likely radionuclide travel from the host rock to the accessible environment. Therefore, the evidence indicates that this favorable condition is not present at Yucca Mountain.

6.3.1.8.4 Potentially adverse conditions

(1) Indications that the site contains naturally occurring materials, whether or not actually identified in such form that (i) economic extraction is potentially feasible during the foreseeable future (ii) or such materials have a greater gross value, net value, or commercial potential than the average for other areas of similar size that are representative of, and located in, the geologic setting.

Evaluation

Resource-potential surveys of the region (Bell and Larson, 1982; Quade and Tingley, 1983) are explained in Section 3.2.4 (and briefly discussed under the favorable condition of this guideline). No energy, metal, or non-metal resources unique to the site vicinity or critical to foreseeable national needs have been identified. The resources identified within the site vicinity are of lower value than similar resources in surrounding regions. On the basis of the preliminary information discussed in sections

3.2.4.2 and 3.2.4.3, Yucca Mountain is not considered to have any potential for the development of natural resources under foreseeable economic conditions and extraction techniques. As pointed out under potentially adverse condition 2, Section 6.3.1.1 (Geohydrology), some water resources are present. However, depths to ground water, topographic conditions, soil unsuitability, and land-use restrictions at the repository site limit the availability and attractiveness of this ground-water resource now and in the future.

Conclusion

Yucca Mountain has no energy or mineral resources for which economic extraction is potentially feasible in the foreseeable future. No resources are known to be present at Yucca Mountain that have greater commercial potential than other areas in its geologic setting. The site does not possess water resources that would meet the criteria stated in the potentially adverse condition. Therefore, the evidence indicates that this potentially adverse condition is not present at Yucca Mountain.

(2) Evidence of subsurface mining or extraction for resources within the site if it could affect waste containment or isolation.

Evaluation

The resource-potential survey of the region did not identify any evidence of significant mining-related operations at the Yucca Mountain site. The entire area has been mapped by the U.S. Geological Survey, and no evidence of significant subsurface mining has been reported. There is little likelihood that unknown excavations other than shallow prospecting pits exist at the site.

Conclusion

There has been no subsurface mining or extraction for resources at Yucca Mountain. Therefore, the evidence indicates that this potentially adverse condition is not present at Yucca Mountain.

(3) Evidence of drilling within the site for any purpose other than repository-site evaluation to a depth sufficient to affect waste containment and isolation.

Evaluation

Before waste storage investigations began, two boreholes existed in the area of the proposed site: Well J-13, which is 7 kilometers (4 miles) southeast of the site, and Well J-12, which is approximately 15 kilometers (9 miles) to the northeast. The site is in an area of federally controlled lands, most of which were restricted in the early 1950s to prevent public access. Furthermore, the entire area has been mapped by the U.S. Geological Survey. Consequently, there is little likelihood that unknown wells, boreholes, or excavations other than shallow prospecting pits exist at the site.

Conclusion

There has been no drilling at Yucca Mountain except that for evaluation of the potential repository site. Therefore, the evidence indicates that this potentially adverse condition is not present at Yucca Mountain.

(4) Evidence of a significant concentration of any naturally occurring material that is not widely available from other sources.

Evaluation

The resource-potential survey found no indication of material or resources that are unique to the site or critical to national needs (see favorable condition 1 for this guideline). Significant mineralization does not generally occur within the type of volcanic rock present in the area of Yucca Mountain. Furthermore, the survey indicated that any material resources found in the site vicinity are also found outside this area. Those outside the area typically have more economic value or are more easily extractable.

Conclusion

There is no evidence of any significant concentration of potentially valuable natural resources at Yucca Mountain that are not widely available from other sources. Therefore, the evidence indicates that this potentially adverse condition is not present at Yucca Mountain.

(5) Potential for foreseeable human activities--such as ground-water withdrawal, extensive irrigation, subsurface injection of fluids, underground pumped storage, military activities, or the construction of large-scale surface-water impoundments--that could adversely change portions of the ground-water flow system important to waste isolation.

Evaluation

The potential for extensive ground-water extraction at or near the site is evaluated in detail in potentially adverse condition 2 of Section 6.3.1.1 (Geohydrology). Although potable ground water is present beneath Yucca Mountain, future generations are not likely to drill and extract water from the top of Yucca Mountain, because drilling and extraction would be easier and more economical in the surrounding area. Extensive pumping of Well J-13, which is 7 kilometers (4 miles) southeast of the Yucca Mountain site in Jackass Flats and draws water from the tuffaceous aquifers, has not resulted in measurable regional declines in the water table. This suggests that ground-water extraction in Jackass Flats would not likely induce significant changes in the ground-water flow system. Furthermore, extensive pumping and drawdown of the water table would improve the isolation potential of the site because it would increase the thickness of the unsaturated zone, resulting in longer travel times to the accessible environment. The depth of the water table and rock conditions at Yucca Mountain would make underground pumped-storage schemes uneconomical. Also, because of the low energy- and mineral-potential of the Yucca Mountain site, it is considered unlikely that any commercial or industrial development that would use water, or require subsurface injections of fluids, would be located in the area. No military activities that affect the ground-water system are foreseen.

Conclusion

The Yucca Mountain area has very limited potential for the large-scale development of any kind of water resources; consequently, modification of the ground-water flow system is unlikely. Water use or waste-fluid production by commercial resource development is not likely in the area. Furthermore, any changes that increase the thickness of the unsaturated zone are likely to be favorable to waste isolation. Therefore, the evidence indicates that this potentially adverse condition is not present at Yucca Mountain.

6.3.1.8.5 Disqualifying conditions

A site shall be disqualified if--

(1) Previous exploration, mining, or extraction activities for resources of commercial importance at the site have created significant pathways between the projected underground facility and the accessible environment, or;

Evaluation

Thorough examination of the Yucca Mountain site and comprehensive searches of literature and mining claim files have disclosed no evidence of ground-disturbing activities. Searches have included the following:

1. Archaeological field surveys over more than 28 square kilometers (11 square miles) for historical artifacts, prospects, or other indicators of resource extraction at the site (Pippin et al., 1982; Pippin, 1984).

2. A resource-potential survey including searches of mining literature and claim files for records of past interest in, or activity at, the site (Bell and Larson, 1982; Quade and Tingley, 1983).

3. Geologic mapping of the entire area by the U.S. Geological Survey (Christiansen and Lipman, 1965; Lipman and McKay, 1965; Scott and Bonk, 1984).

It is extremely unlikely that unknown excavations exist at the site. The site is in an area of federally controlled lands, most of which were restricted in the early 1950s to prevent public access and thereby excluded from the development of even small-scale mining operations.

Conclusion

There have been no previous exploration, mining, or extraction activities for resources at the Yucca Mountain site. No significant pathways have been created between the projected underground facility and the accessible environment. Therefore, on the basis of the above evaluation, the available evidence does not support a finding that the site is disqualified (level 1).

(2) Ongoing or likely future activities to recover presently valuable natural mineral resources outside the controlled area would be expected to lead to an inadvertent loss of waste isolation.

Evaluation

As described in Chapter 3, Bell and Larson (1982) investigated the resource potential around Yucca Mountain and identified no energy, metal or nonmetal resources unique to the site vicinity or critical to foreseeable national needs. Figure 6-23 shows the location of metal deposits, industrial minerals, and thermal waters in the vicinity of Yucca Mountain. Minor amounts of uranium have been reported west of Yucca Mountain at Bare Mountain, but no uranium mines or prospects have been developed. The nearest mining activity is about 5 kilometers (3 miles) west of Yucca Mountain. Industrial minerals are being extracted from shallow mines in that area.

Conclusion

Only shallow mining of industrial minerals now exists in the vicinity of Yucca Mountain. No resources have been identified that would be likely to cause increased mining activities. There are no ongoing or expected future activities to recover presently valuable natural mineral resources outside the controlled area that could be expected to lead to inadvertent loss of waste isolation. Therefore, the evidence does not support a finding that the site is disqualified (level 1).

6.3.1.8.6 Evaluation and conclusion for the qualifying condition on the natural resources part of the postclosure human interference technical guideline

Evaluation

A thorough examination of the resource potential for Yucca Mountain has been made, including geologic mapping of the area and a resource-potential survey. These studies indicate no known natural resources or naturally occurring materials that currently have significant commercial value. Furthermore, they have not identified any resources or materials that are likely to become commercially attractive in the future. Evidence of subsurface drilling, mining, or exploration has not been found. Extensive groundwater withdrawal near or at the site would be likely to improve the isolation potential by increasing the travel times to a deeper water table.

Permanent markers that would warn future generations of the danger of the repository can be installed at Yucca Mountain. Furthermore, some of the characteristics of the site, such as the extremely arid climate and the low population density in the surrounding region, are favorable to the preservation of permanent markers. No site-specific factors that would be likely to compromise the effectiveness of such markers have been identified, and none are likely to be present.

Conclusion

Currently, the Yucca Mountain site has no known valuable natural resources, and no natural resources have been identified that are likely to become sufficiently valuable in the foreseeable future that they would encourage interference activities that could lead to unacceptable releases of radionuclides. The only resource of value is ground water, and extensive withdrawal could favorably affect portions of the ground water flow system important to isolation by increasing the thickness of the unsaturated zone. Extreme aridity and low population density help to guarantee that an effective system of permanent markers can be installed. Therefore, on the basis of the above evaluation, the evidence does not support a finding that the site is not likely to meet the qualifying condition for postclosure human interference (level 3).

6.3.1.8.7 Plans for site characterization

The effects of ground-water withdrawal in various parts of the area surrounding the Yucca Mountain site will be better established by hydrologic information collected during site characterization. Additional data on hydraulic gradients and relationships amoung ground-water basins and sub-basins will be particularly useful for refining regional hydrologic models. The need for additional information on resource potential will be evaluated during site characterization.

6.3.2 POSTCLOSURE SYSTEM GUIDELINE (10 CFR 960.4-1)

6.3.2.1 Introduction

The qualifying condition for this guideline is as follows:

The geologic setting at the site shall allow for the physical separation of radioactive waste from the accessible environment after closure in accordance with the requirements of 40 CFR Part 191, Subpart B, as implemented by the provisions of 10 CFR Part 60. The geologic setting at the site will allow for the use of engineered barriers to ensure compliance with the requirements of 40 CFR Part 191 and 10 CFR Part 60.

The postclosure system guideline defines general requirements for the performance of the entire waste disposal system after the repository has been closed. These performance requirements are based generally on the objective of protecting the health and safety of the public until the radioactivity of the waste has decreased to safe levels (i.e., 1,000 years) and specifically on the requirements of the U.S. Environmental Protection Agency (EPA) 40 CFR Part 191 (1985) and the Nuclear Regulatory Commission (NRC) 10 CFR Part 60 (1983).

The waste disposal system consists of a natural barrier subsystem (the geologic setting at the site) and an engineered barrier subsystem (the waste package and the mined repository excluding boreholes, shafts, and seals). The role of engineered barriers as part of the total waste disposal system is recognized by both the EPA and the NRC; both of these agencies have established specific performance requirements or objectives in 40 CFR Part 191 (1985) and 10 CFR Part 60 (1983), respectively. However, the objective of the siting guidelines is to ensure the selection of a site that has the required capability for waste isolation. For this reason, the merits of the geologic setting at the site have been evaluated independently from any engineered features that would be used, and engineered barriers have been considered only where necessary to establish a reference condition for evaluating the potential effectiveness of particular site conditions (Section 6.4.2).

At this stage of site investigations, the data that have been collected and analyzed are insufficient for assessing the performance of the total waste disposal system, its subsystems, and components or the uncertainties associated with each component. Such an assessment will be conducted after site characterization and the final design of the repository have been completed. Therefore, final conclusions about the ability of the Yucca Mountain site to comply with the postclosure system guideline are neither possible nor expected at present. It is, however, possible to make judgments, based on the quantitative and qualitative evaluations reported in this section, about the degree of confidence that the site will indeed be shown to comply with the system guideline after site characterization.

6.3.2.2 Evaluation of the Yucca Mountain site

The approach used in evaluating the Yucca Mountain site against the postclosure system guideline is both quantitative and qualitative. The quantitative approach predicts the quantity of radionuclides that would be released from the repository into the accessible environment during the next 10,000 years if present site conditions persist. The assumption about present conditions persisting in the future is necessitated by the unavoidable uncertainty about specific future conditions at Yucca Mountain (or any site). The predictions are based on limited information about the site and simple modeling techniques. Their sole purpose is to establish the general range of expected site performance.

The qualitative approach balances the potential influences of the favorable and the potentially adverse conditions in the technical guidelines. This approach is judgmental because the relative importance of particular favorable and potentially adverse conditions must be weighed in relation to their potential effects on the behavior in the context of the overall setting at Yucca Mountain. Nonetheless, evaluations of the site against these conditions can strongly indicate whether a site has the features needed for long-term waste isolation.

The data on which the quantitative and qualitative analyses are based are summarized in sections 6.3.1.1 through 6.3.1.8. The analyses of Sinnock et al. (1984) and Thompson et al. (1984) supplement the analyses in this section and provide additional detail. Sinnock et al. (1984) and Thompson et al. (1984) also used early estimates of ground-water flux (Sass and Lachenbruch, 1982) and estimates of matrix diffusion (Travis et al., 1984) in some of their calculations.

6.3.2.2.1 Quantitative analyses

In Section 6.4.2, the predicted performance of simple system and subsystem models is informally compared with six regulatory criteria specified by the U.S. Environmental Protection Agency (EPA) (40 CFR Part 191, 1985) and the Nuclear Regulatory Commission (NRC) (10 CFR Part 60, 1983): the waste-containment requirements of 40 CFR 191.13, the individual protection requirements of 40 CFR 191.16, the ground-water protection requirements of 40 CFR 191.16, the ground-water travel time specified in 10 CFR 60.113, the performance objective for the waste package specified in 10 CFR 60.113, and the fractional radionuclide-release rate from the engineered barrier system specified in 10 CFR 60.113 (see Table 6-51 in Section 6.4.2). The comparison shows that the Yucca Mountain site, as described by the simple model discussed in Section 6.4.2, would meet all of these criteria. In regard to the isolation requirements of 40 CFR 191.13, the cumulative release of radioactivity (in curies) to the accessible environment for the first 10,000 years after repository closure is predicted to lie well below the EPA limits for a wide range of the fractional radionuclide-release rates from the engineered-barrier system. As a corollary, releases to the saturated zone under Yucca Mountain are predicted to be zero for the first 10,000 years, and the modeled system meets the ground-water protection requirements of 40 CFR 191.16. The expected ground-water travel time is greater than 10,000, with an average travel time of 43,405 years; hence the modeled system also meets the performance objective of a 1,000-year pre-waste-emplacement ground-water travel time in 10 CFR 60.113. The lifetime of the model waste package is expected to exceed 3,000 years, which is substantially longer than the performance objective (300 to 1,000 years) of 10 CFR 60.113. Finally, for the upper bound flux estimate, time-averaged fractional radionuclide release rates from the engineered barrier system are predicted to be 1 part in 100 million per year or less, which is only one-thousandth of the limit specified in 10 CFR 60.113, a release of 1 part in 100,000 of the waste species present 1,000 years after repository closure.

Other analyses that supplement the conclusions presented here have been made and described in detail by Thompson et al. (1984) and Sinnock et al. (1984). Thompson et al. (1984) completed their study before evidence became available that the upper bound on flux of ground water at the repository level is probably 0.5 millimeter (0.02 inch) per year (Section 6.3.1.1.5). They chose a vertical flux through the repository of 5 millimeters (0.2 inch) per year as the midpoint of the flux range (1 to 10 millimeter (0.04 to 0.4 inch) per year) suggested by early studies of Sass and Lachenbruch (1982). The release of radionuclides into this flux was assumed to begin 300 years after waste emplacement. The release rate was assumed to be determined by an overall waste-dissolution rate of one part in 100,000 per year of the total mass of the waste (in the form of both spent fuel and high-level waste converted to borosilicate glass). Sorption was the only retardation mechanism assumed to affect radionuclide transport in the moving water. In this study, only two radionuclides, carbon-14 and technetium-99 (both nonsorbing), were predicted to reach the accessible environment (at that time, this was a point 10 kilometers (6.2 miles) horizontally distant from the repository) within 10,000 years. The estimated quantities released from 1,000 metric tons of heavy metal (MTHM) were about 1 curie of carbon-14 and 8 curies of technetium-99. The release limits established by the EPA for these nuclides in 40 CFR Part 191 (1985) are 100 and 10,000 curies per 1,000 MTHM, respectively. Thus, the early quantitative analysis of Thompson et al. (1984) indicated that the site, in and of itself, could limit radionuclide releases to the accessible environment to about 2 percent of those allowed by the EPA standards provided that flow was in the rock matrix.

More recently, Sinnock et al. (1984) analyzed the sensitivity of releases (both from the waste form and to the accessible environment) to variations in the water flux through the repository and to waste-form solubility. Their results indicate that the Yucca Mountain site would comply with the established EPA release limits even if the water flux reached 20 millimeters (0.8 inch) per year, assuming that radionuclide releases from the waste forms are limited by the solubility of uranium oxide and glass and the phenomenon of matrix diffusion (Travis et al., 1984) retards transport in fractures by a factor of at least 100, and perhaps 400. The results of this study also suggest that the NRC limits for the fractional radionuclide release rate from the engineered barrier system can be met without any engineered barriers other than the waste form because the amount of water likely to be in contact with the waste is insufficient to cause higher rates of waste dissolution.

Three conclusions can be derived from the study by Sinnock et al. (1984). First, flux values up to 40 times the current upper bound of 0.5 millimeter (0.02 inch) per year are not expected to cause releases to exceed limits. Second, the unsaturated zone is favorable for waste isolation because waste dissolution is limited by low flux. Third, geochemical retardation (sorption) is not necessary to satisfy performance objectives, and hence the presence of a zeolitized zone beneath the repository horizon provides additional assurance that radionuclide release and transport will not occur even under extreme conditions. However, the study did rely on the phenomenon of matrix diffusion to meet standards at the higher values of flux.

The performance studies summarized above are first steps toward developing confidence in the waste-isolation capability of the geologic setting at Yucca Mountain. They do not substitute for the detailed performance assessment that will be made after data from site characterization become available. These preliminary studies have used analytical and computational tools that are considered valid and reasonable, but have not all been formally validated and verified. Furthermore, these preliminary studies have not considered disruptive events and processes that could alter the expected pattern of waste release (i.e., climatic changes, tectonism, erosion, and human interference). Although some discussion of disruptive events is given in Section 6.4.2, a complete set of disruptive-event scenarios pertinent to Yucca Mountain cannot be identified until site characterization is completed. Many of the favorable and potentially adverse conditions in the guidelines deal with potentially disruptive events. The evaluations in sections 6.3.1.1 through 6.3.1.8 summarize the knowledge, some of which is quantitative, that has been gathered about them.

To compensate for uncertainties caused by limited information about the site and the design of the repository, many of the assumptions used in these preliminary studies are conservative. In particular, the following conservative assumptions should be noted:

1. In some of the studies, no credit was taken for engineered barriers in evaluating the performance of the repository, even though a realistic evaluation cannot be made without considering the contribution of engineered barriers.

2. In some of the studies, the percentage of the total water flux passing through the repository that actually reaches and dissolves the waste was assumed to be much higher than is likely (see the discussion of the geohydrology disqualifying condition in Section 6.3.1.1.5).

3. In all of the studies, a uniform vertical downward flux at the repository level was assumed. No consideration was given to the possible diversion of some or of all the percolating water along the generally longer, horizontal flow paths by stratigraphic or structural features in the rock units below the repository.

4. In some of the earlier studies, the thickness of the unsaturated, highly sorptive tuffaceous beds of Calico Hills was assumed to be only 100 meters (330 feet) for the calculations of flow time and radionuclide transport. However, the thickness of the Calico Hills unit below the proposed repository horizon is 100 to 350 meters (330 to 1,150 feet) (see Figure 6-2).

5. None of the studies took credit for the potential drying effect of heat emitted by the waste on the rocks around the waste-emplacement holes or on water entry into waste disposal containers (see the discussion of the geochemistry second favorable condition in Section 6.3.1.2.3).

In combination, the results obtained using these conservative assumptions lend confidence to the conclusion that, after site characterization, the Yucca Mountain site will be shown to meet the postclosure system guideline (10 CFR 960.4-1(a), 1984).

6.3.2.2.2 Qualitative analysis

The evaluations against the favorable and potentially adverse conditions of the postclosure technical guidelines show that the Yucca Mountain site remains eligible under all of the postclosure technical guidelines and is not disqualified under any of the five postclosure guidelines that contain a disqualifying condition (sections 6.3.1.1 through 6.3.1.8). Conclusions about site suitability will be reevaluated after site characterization, when additional site data and design information are available. These preliminary evaluations lead to different levels of confidence about compliance with each postclosure guideline. The level of confidence is the highest for meeting the guidelines on erosion, dissolution, and human interference; it is only slightly lower for the guidelines on geochemistry and rock characteristics. The potential of the site to meet the guidelines on geohydrology, climate change, and tectonics engenders the most uncertainty. In no instance, however, is the level of confidence low enough to justify a finding that Yucca Mountain does not qualify, or is disqualified, with respect to any of the technical guidelines.

Remaining uncertainties in evaluations of the site against the postclosure technical guidelines stem from the scarcity of data, incomplete understanding of certain natural phenomena, and inability to quantify the likelihood of human intrusion in the distant future. Generally, the more important of these uncertainties are the potential for rapid ground-water flow through fractures and for large rises in the water table in the presence of other potentially adverse conditions at the site. The principal natural phenomena for which incomplete understanding leads to uncertainty are ground-water flow, expected climatic changes, oxidizing conditions in the unsaturated zone, and tectonic processes. These and other phenomena that might significantly affect waste isolation are evaluated in the appropriate sections in this chapter. The implications of the potential effects on waste isolation are not fully understood at present, although certain preliminary observations can be made.

Oxidizing conditions around the waste might seem to indicate an increased potential for releases of radionuclides from the engineered barrier system, although these conditions are not expected to cause serious problems (see discussion of potentially adverse condition 3 in Section 6.3.1.2.4). On the other hand, the current information about the water flux and geochemical retardation at Yucca Mountain suggests that they will decrease the potential for releases of radionuclides to the accessible environment. As discussed below, the low flux expected for the unsaturated zone at Yucca Mountain would increase travel times and limit waste-dissolution rates to extremely low levels. The presence of engineered waste disposal containers would provide additional assurance that the oxidizing conditions, in particular, will not result in unsatisfactory performance.

The possibility of adverse effects due to tectonic activity can be examined by studying their effects on ground-water flow. The parametric analyses by Sinnock et al. (1984) included evaluations of performance under ground-water fluxes of up to 20 millimeters (0.8 inch) per year, which is at least 40 times higher than the maximum flux expected at and below the repository level. Even such high fluxes did not cause the predicted releases of radionuclides at the accessible environment to exceed the proposed U.S. Environmental Protection Agency standards. Current estimates of the most likely flux passing through the host rock at Yucca Mountain indicate that fracture flow is presently not significant and further tectonically induced increases in fracture density in the host rock would not be likely to affect radionuclide migration. Furthermore, the rocks of Yucca Mountain have been subjected to active tectonism for millions of years and are already highly fractured in the units that are brittle enough to fracture. Therefore, any increase in fracturing is expected to be minor, unless the tectonic regime were to change drastically. Overall, tectonic processes will probably have negligible effects on flow mechanisms in the absence of extreme and rapid climatic changes.

The effects of possible climatic changes represent a area of concern. Possible increases on unsaturated zone flux, increased water table altitudes, and changes in transport processes in both the unsaturated and saturated zones will be carefully evaluated during site characterization. To date, it appears that possible climate changes over the next 10,000 years are unlikely to cause significant changes in the potential for radionuclide releases to the accessible environments.

Human intrusion might seem to present a potential for release of radionuclides that would exceed the regulatory limits. In principle, the presence of potable ground water beneath the site may induce future generations to drill near the repository site to obtain water. However, no mechanisms whereby this drilling could significantly change the total amount of waste released to, or transported by, the hydrologic system have been identified to date. Moreover, concern about the potential for human intrusion is diminished by the great depth to the water table.

In summary, the hydrologic conditions alone are believed to be sufficient to compensate for the potentially adverse conditions outlined above. Other favorable conditions for rock characteristics, erosion, and human interference reinforce the belief that the waste-isolation capabilities of Yucca Mountain are not likely to be seriously impaired in the future.

Therefore, even though Yucca Mountain possesses some potentially adverse conditions, the current understanding of these conditions leads to the conclusion that they will not cause significant risks for future generations. This conclusion must be more firmly established by quantitative analyses of both the likelihood (when possible) and the consequences of the potentially adverse conditions. In addition, the satisfactory performance inferred from the presence of the favorable conditions currently thought to exist at Yucca Mountain must be confirmed with more comprehensive analyses. Proceeding in parallel with site characterization, such analyses would identify the most important conditions for consideration and provide a documented and realistic assessment of the risks posed by a repository at Yucca Mountain.

6.3.2.3 Summary and conclusion for the qualifying condition on the postclosure system guideline

Preliminary quantitative performance studies support the conclusion that a repository at Yucca Mountain qualifies for site characterization under the postclosure system guideline, 10 CFR 960.4-1(a) (1984), because it would meet the U.S. Environmental Protection Agency standards in 40 CFR Part 191 (1985) if present hydrologic, geologic, and geochemical conditions (as presently understood) persist for the next 10,000 years. Furthermore, it is likely that the Nuclear Regulatory Commission limits on release rates from the engineered barrier system (i.e., 1 part in 100,000) could be met. These conclusions were drawn from several independent preliminary quantitative analyses and qualitative judgments based on site conditions.

The effects of potentially disruptive events or processes, such as climate changes, tectonism, extreme erosion, and human interference have not all been addressed by quantitative analyses, but no realistic and likely mechanisms for repository failure through such events or processes have been identified to date. Qualitatively, the Yucca Mountain site is judged to be qualified under all eight of the postclosure technical guidelines and is not disqualified under any of the five guidelines that contain a disqualifying condition. This conclusion is supported by the overall balance between the favorable and the potentially adverse conditions identified at Yucca Mountain. Although the level of confidence about the existence and the effect of individual site conditions does vary, the favorable aspects of a very small water flux and good geochemical retardation contribute to the high degree of confidence about the ability of the geologic setting to isolate the waste. Therefore, the evidence does not support a finding that the site is not likely to meet the qualifying condition for the postclosure system guideline (level 3).

6.3.3 PRECLOSURE TECHNICAL GUIDELINES

This section presents preliminary evaluations of the Yucca Mountain site against the preclosure technical guidelines that require site characterization for the demonstration of compliance. These technical guidelines are related to the preclosure system guideline on the ease and cost of repository siting, construction, operation, and closure (10 CFR 960.5-1(a)(3), 1984). They are concerned with surface and rock characteristics and hydrologic and tectonic conditions.

6.3.3.1 Surface characteristics (10 CFR 960.5-2-8)

6.3.3.1.1 Introduction

The qualifying condition for this guideline is as follows:

The site shall be located such that, considering the surface characteristics and conditions of the site and surrounding area, including surface-water systems and the terrain, the requirements specified in Section 960.5-1(a)(3) can be met during repository siting, construction, operation, and closure.

The surface characteristics technical guideline is one of several preclosure guidelines under the heading entitled ease and cost of construction, operation, and closure. The objectives of this guideline are to ensure that (1) adverse surface characteristics will not require any technology other than that reasonably available for siting, construction, operation, and closure of a repository, and (2) the associated costs will not be unreasonable relative to other available and comparable siting options.

The concerns to be addressed under this guideline are related primarily to topographic features that control placement of or otherwise impact surface facilities. Special measures may be necessary for repository construction, operation, and closure in sites prone to periodic flooding, located in rugged terrain, or with other adverse surface features.

This guideline consists of two favorable conditions, one potentially adverse condition, and one qualifying condition. The Yucca Mountain site is evaluated with respect to each of these conditions in the following sections, and Table 6-38 summarizes the pertinent findings for these conditions.

6.3.3.1.2 Data relevant to the evaluation

The candidate locations that were evaluated as potential sites for the surface facilities of the repository are on the eastern side of Yucca Mountain (Jackson, 1984). A reference conceptual site was selected for planning purposes (Neal, 1985). The data needed to describe the surface characteristics were obtained primarily from 1:24,000 topographic maps with 6-meter (20-foot) contour spacing (USGS, 1961) and high-resolution aerial photographs (e.g., Figure 2-2). The topographic data were evaluated together with surface hydrography in order to determine the flood potential along the Fortymile Wash drainage basin (Squires and Young, 1984). Geomorphic observations also have been made to determine the relative ages of surfaces and thereby allow an assessment of the general stability of these surfaces during the operational period.

Flood peaks have been estimated for the 100-year, the 500-year, and the regional maximum (most intense) floods for the eastern part of Yucca Mountain and Fortymile Wash (Squires and Young, 1984). The prediction of the regional maximum flood was based on data from floods elsewhere in Nevada and in surrounding states. The water depths predicted for major channels during flood peaks are based on the estimated runoff produced during extreme storm events and the capacity of the drainage system.

Assumptions and data uncertainties

Uncertainty in topographic data originates in the accuracy of the photogrammetric process and field survey data. The accuracy of topographic data requires an evaluation relative to the purposes for which they are used. The reference topographic maps (USGS, 1961) comply with National Map Accuracy Standards and are adequate for preliminary repository planning. The aerial photographs and associated ground-survey control are sufficient to provide the higher-detail maps that will be required for construction. The flood predictions and regional geomorphic interpretations are partly qualitative, but they are based on prevailing scientific methods. No site-specific flood or runoff data are currently available for Yucca Mountain.

Table 6-38. Summary of analyses for Section 6.3.3.1; surface characteristics (10 CFR 960.5-2-8)

Condition	Department of Energy (DOE) finding
FAVORABLE CONDITIONS	
(1) Generally flat terrain.	The evidence indicates that this favorable condition is present at Yucca Mountain: surface facilities and access routes will be located in areas with generally flat terrain.
(2) Generally well drained terrain.	The evidence indicates that this favorable condition is present at Yucca Mountain: there is a well-established drainage system; porous alluvial soils are present and the water table is deep; the area will not pond water.
POTENTIALLY ADVERSE CONDITION	
Surface characteristics that could lead to flooding of surface or underground facilities by the occupancy and modification of floodplains, the failure of existing or planned man-made surface-water impoundments, or the failure of engineered components of the repository.	The evidence indicates that this potentially adverse condition is present at Yucca Mountain: arroyo drainage system is subject to short periods of localized flooding during rare extreme storms; potential exists for minor flooding due to sheet flow during infrequent extreme storms, although standard drainage control measures are considered adequate to protect surface and underground facilities.
QUALIFYING CONDITION	
The site shall be located such that, considering the surface characteristics and conditions of the site and surrounding area, including surface-water systems and the terrain, the requirements specified in Section 960.5-1(a)(3) can be met during repository construction, operation, and closure.	Available evidence does not support the finding that the site is not likely to meet the qualifying condition (level 3): surface facilities would be located on the flat eastern slopes of Yucca Mountain; areas are well drained but subject to short periods of localized sheet flow during rare extreme storms.

6.3.3.1.3 Favorable conditions

(1) Generally flat terrain.

Evaluation

The reference conceptual site for the surface facilities of the repository and exploratory shaft is on the eastern side of Yucca Mountain (Neal, 1985). The site is generally flat and covered with alluvium derived from adjacent highlands. The surface slope is less than 5 percent and, in several places, less than 3 percent. Thus, even though terrain directly above the area proposed for the underground facility is rugged with established drainage channels, the surface facilities and access routes would be located in an area of generally flat terrain.

Access to the surface facilities would be provided by rail and highway. Detailed descriptions of the characteristics of these access routes are given in Section 5.3. A major design consideration is protection for the bridge piers and abutments that would be built across Fortymile Wash because large volumes of water and debris move down the wash during severe storms. The necessary drainage control measures are not major, but the bridge piers and abutments must be well designed to ensure protection against damage.

Conclusion

The surface facilities, shafts, and the access routes to them can be located in generally flat areas with slopes of less than 5 percent. Therefore, the evidence indicates that this favorable condition is present at Yucca Mountain.

(2) Generally well-drained terrain.

Evaluation

The drainage systems at Yucca Mountain are well developed; they have been identified from topographic maps (USGS, 1961) and aerial photographs. The conditions that contribute to effective and rapid drainage include the porous alluvial soils and the eastward dipping slopes. The average depth to the water table is 500 to 750 meters (1,640 to 2,460 feet) in the Yucca Mountain area (Section 6.3.1.1).

Conclusion

Yucca Mountain has a well-established drainage system. The consistency of slope direction coupled with the evenness of the surfaces, the depth to the water table, and the porous nature of the alluvial soils, suggest that the area will not pond water. Therefore, the evidence indicates that this favorable condition is present at Yucca Mountain.

6.3.3.1.4 Potentially adverse condition

Surface characteristics that could lead to the flooding of surface or underground facilities by the occupancy and modification of flood plains, the failure of existing or planned man-made surface-water impoundments, or the failure of engineered components of the repository.

Evaluation

The current reference location for the surface facility (Neal, 1985) is entirely outside the main-channel flood zones predicted for the 100-year flood (Squires and Young, 1984). Parts of the reference location would be affected by the 500-year and regional maximum floods predicted by Squires and Young (1984). However, these areas can be protected by standard drainage control measures such as channel lining and by diversion during construction. Neither lining nor diversion is expected to be a major cost. Moreover, the repository at Yucca Mountain is not expected to contain any engineered components whose failure could lead to significant flooding of the underground facility.

The washes emerging from Yucca Mountain have generally steep slopes and are capable of moving large volumes of water and debris, including large boulders. The proposed exploratory shaft site in Coyote Wash is within 50 meters (160 feet) of a small colluvial slump debris-flow deposit. Similar deposits are probably present elsewhere at Yucca Mountain, and such depositional sites will be avoided in choosing a location for repository structures and ventilation shafts. These facilities will not be placed in potentially adverse locations; alternatively, drainage control measures will be used. Relocation can be accomplished at minimal, cost; if any, likewise, protective measures such as channel lining or diversion are not expected to add significantly to the cost of the repository. There are no nearby existing or planned man-made surface-water impoundments that could flood a repository at Yucca Mountain. The engineered components of the repository are not likely to fail because their design and specifications will be independently examined by the Nuclear Regulatory Commission and adequate safety factors will be used during design, construction, and operation.

The flooding potential predicted for the Fortymile Wash system is based on conditions that can be expected during the rare but extreme meteorological events that occur in the area (Section 6.2.1.4). These predictions are derived from data for similar events in the region. The flood-potential maps are reasonable first estimates that can be used in planning, and the maps will be revised on the basis of additional field geomorphic data. To verify the flooding predictions, field investigations, including the collection of runoff data, are under way. These investigations will include the mapping of areas that were subject to flooding during Holocene time and a calculation of the probable maximum flood (PMF) during site characterization.

Conclusion

The arroyo drainage system leading away from Yucca Mountain is subject to localized flooding and debris flows during rare extreme storms. These storms could result in flooding of the surface or underground facilities due to possible sheet flow. However, the impacts of this infrequent localized flooding can be mitigated during repository siting, construction, operation, and closure. On the basis of the potential for sheet flow, the evidence indicates that this potentially adverse condition is present at Yucca Mountain.

6.3.3.1.5 Evaluation and conclusion for the qualifying condition on the preclosure surface characteristics guideline

Evaluation

The conclusions about the suitability of the surface characteristics at the Yucca Mountain site are largely qualitative; they are based on the engineering and scientific judgment of the many professional civil engineers and geologists who have examined the available topographic, geomorphic, and flood potential data for the site.

The alluvial area on the eastern side of Yucca Mountain is well drained but also subject to overflows of water from the existing arroyos during extreme storm events (100-year, 500-year, and regional maximum floods). As indicated by their recurrence intervals, these floods are very infrequent and of such short duration that they would not significantly affect the siting, construction, operation, and closure of a repository. The effects of these extreme events, as well as debris flows and sheet flow, can be readily mitigated using standard drainage control measures.

Conclusion

The surface and underground facilities can be located where the surface characteristics would not adversely affect either the ease or the cost of repository siting, construction, operation, and closure. The current reference surface facility location is well drained but may be subject to infrequent floods and sheet flow whose impacts can be mitigated easily using standard drainage control measures without incurring major costs. Therefore, on the basis of the above evaluation, the evidence does not support a finding that the site is not likely to meet the qualifying condition for preclosure surface characteristics (level 3).

6.3.3.1.6 Plans for site characterization

Site-specific meteorological data will be obtained and should allow better planning for the drainage control measures that are needed to adequately protect the surface and underground facilities. Field investigations and laboratory testing to determine soil and bedrock properties will be conducted to determine improved locations for the repository surface facilities.

6.3.3.2 Rock characteristics (10 CFR 960.5-2-9)

6.3.3.2.1 Introduction

The qualifying condition for this guideline is as follows:

The site shall be located such that (1) the thickness and lateral extent and the characteristics and composition of the host rock will be suitable for accommodation of the underground facility; (2) the repository construction, operation and closure will not cause undue hazard to personnel; and (3) the requirements specified in Section 960.5-1(a)(3) can be met.

The objective of this guideline is to ensure that due consideration is given to the host-rock characteristics that may affect (1) the ease and cost of repository siting, construction, operation, and closure, and (2) the safety of repository workers. Among those characteristics are the thickness and lateral extent of the host rock, geomechanical properties that are favorable for the stability of underground openings, and conditions that allow the construction of shafts and the underground facility with reasonably available technology.

The preclosure rock characteristics guideline consists of two favorable conditions, five potentially adverse conditions, one disqualifying condition, and one qualifying condition. The evaluations reported below are summarized on Table 6-39 for all conditions except the disqualifying condition.

6.3.3.2.2 Data relevant to the evaluation

Summary of available data

Available data indicate that rock with acceptable characteristics for locating an underground facility are present beneath Yucca Mountain (Sinnock and Fernandez, 1982; Sinnock et al., 1986; Mansure and Ortiz, 1984). Detailed surface mapping (Scott and Bonk, 1984) and core samples from drill holes led to the initial identification of four potential horizons for the underground facility; samples from the potential host rock obtained from core samples have been analyzed for mineral content (Bish et al., 1982, 1984) and for geoengineering properties (Lappin, 1980a,b; Lappin et al., 1982; Dravo Engineers, Inc., 1984; Price et al., 1982a,b; Price, 1983). A three-dimensional geologic model of Yucca Mountain is presented in Nimick and Williams (1984). Additional data are available on borehole and tunnel tests and measurements in tuff (Healy et al., 1984; Tyler and Vollendorf, 1975; Ellis and Ege, 1976; and Warpinski et al., 1978).

The relative suitabilities of the four potential horizons have been compared on the basis of minability, excavation stability, maximum capacity for gross thermal loading, far-field thermomechanical responses, and potential ground-water travel times (Johnstone et al., 1984). Geoengineering properties of the four horizons are reported in Tillerson and Nimick (1984).

Table 6-39. Summary of analyses for Section 6.3.3.2; rock characteristics (10 CFR 960.5-2-9)

Condition	Department of Energy (DOE) finding
FAVORABLE CONDITIONS	
(1) A host rock that is sufficiently thick and laterally extensive to allow significant flexibility in selecting the depth, configuration, and location of the underground facility.	The evidence indicates that this favorable condition is not present at Yucca Mountain: significant lateral flexibility cannot be claimed until site-characterization data are available.
(2) A host rock with characteristics that would require minimal or no artificial support for underground openings to ensure safe repository construction, operation, and closure.	The evidence indicates that this favorable condition is present at Yucca Mountain: minimal artificial means are required to support similar tuffs at the NTS; a similar approach should ensure safe repository construction, operation, and closure.
POTENTIALLY ADVERSE CONDITIONS	
(1) A host rock that is suitable for repository construction, operation, and closure, but is so thin and laterally restricted that little flexibility is available for selecting the depth, configuration, or location of an underground facility.	The evidence indicates that this potentially adverse condition is present at Yucca Mountain: significant lateral flexibility cannot be claimed.
(2) In situ characteristics and conditions that could require engineering measures beyond reasonably available technology in the construction of the shafts and underground facility.	The evidence indicates that this potentially adverse condition is not present at Yucca Mountain: shafts and underground facility can be constructed using proven, standard methods.

Table 6-39. Summary of analyses for Section 6.3.3.2; rock characteristics (10 CFR 960.5-2-9) (continued)

Condition	Department of Energy (DOE) finding
(3) Geomechanical properties that could necessitate extensive maintenance of the underground openings during repository operation and closure.	The evidence indicates that this potentially adverse condition is not present at Yucca Mountain: conventional rock bolts and wire mesh are expected to provide adequate support and require minimal maintenance.
(4) Potential for such phenomena as thermally induced fracturing, the hydration and dehydration of mineral components, or other physical, chemical, or radiation-related phenomena that could lead to safety hazards or difficulty in retrieval during repository operation.	The evidence indicates that this potentially adverse condition is not present at Yucca Mountain: welded tuff is expected to have sufficient physical and chemical stability to ensure safety and retrievability; no potentially hazardous physical, chemical, or radiation-related phenomena have been identified.
(5) Existing faults, shear zones, pressurized brine pockets, dissolution effects, or other stratigraphic or structural features that could compromise the safety of repository personnel because of water inflow or construction problems.	The evidence indicates that this potentially adverse condition is not present at Yucca Mountain: an unsaturated zone repository is not expected to have water in flow, and stratigraphic and structural features are not expected to compromise safety.
QUALIFYING CONDITION	
The site shall be located such that (1) the thickness and lateral extent and characteristics and composition of the host rock will be suitable for accommodation of the underground facility; (2) repository construction, operation, and closure will not cause undue hazard to personnel; and (3) the requirements specified in Section 960.5-1(a)(3) can be met.	Available evidence does not support the finding that the site is not likely to meet the qualifying condition (level 3): thickness and lateral extent of host rock is expected to provide adequate, but not significant flexibility for the lateral layout and reasonable flexibility for vertical repository positioning; no rock characteristics that could cause undue hazards to personnel have been identified or are expected to be encountered.

Ground support requirements have been evaluated using mining experience at tunnel excavations of the Nevada Test Site (NTS) in formations similar to the devitrified, densely welded tuffs of the Topopah Spring Member at Yucca Mountain (Dravo Engineers, Inc., 1984; Tibbs, 1985; Ortego, 1985). Small-diameter-heater experiments have been conducted in tuff at one of these excavations to determine the thermomechanical rock properties (Zimmerman, 1983).

Information from Kendorski et al. (1984) is used to evaluate the long-term stability of shotcrete lining in tunnels. Accident statistics from the hardrock metal-mining industry and from the Nevada Test Site excavations are used in the discussion of operational safety (Schueler, 1985). Information on accident experience in tunnels at the NTS is available in Dunnam (1985) and Tibbs (1985). The concepts of the safety orders presented in DOE (1981) and the California Department of Mines safety orders have been incorporated into the safety standards and enforcement practices now used for tunnel construction at the NTS.

Assumptions and data uncertainties

The analyses of the suitability of rock characteristics are based primarily on data from surface reconnaissance and boreholes. No major excavations have been made at the Yucca Mountain site, and there is no experience with excavations in the proposed horizon elsewhere in the area. However, extensive tunnel systems have been excavated in the bedded and welded tuffs at Rainier Mesa on the NTS. As part of the Nevada Nuclear Waste Storage Investigations Project, in situ experiments have been initiated in one tunnel in Rainier Mesa (G-Tunnel) in a welded tuff unit with some characteristics that are similar to those expected in the repository horizon. Data collected from drill holes have been used in the preliminary stability analysis for the proposed exploratory shaft (Hustrulid, 1984) which will penetrate the potential repository horizons. Data obtained from the exploratory shaft and related boreholes will significantly expand the existing data base that is being used for conceptual design of the repository and design analyses. As part of the preliminary conceptual design and related work, a study was made addressing how variations in geologic and geophysical properties impact repository planning and design (Dravo Engineers, Inc., 1984). New information obtained during site characterization may lead to some changes in the design of the repository, but these changes are expected to be within the limits expressed in the original reference repository design (Jackson, 1984). The thermomechanical modeling of the potential repository horizons (Johnstone et al., 1984) is considered a preliminary evaluation. Validation of this model and additional modeling will be addressed during site characterization. The degree of confidence in both the existing data for the site and the analyses made with the data is considered more than sufficient for a preliminary evaluation against the preclosure guideline on rock characteristics.

6.3.3.2.3 Favorable conditions

(1) A host rock that is sufficiently thick and laterally extensive to allow significant flexibility in selecting the depth, configuration, and location of the underground facility.

Evaluation

Flexibility in locating the repository is important because sufficient options should be available to construct the underground facility away from areas of geologic anomalies, should they be found. No anomalies are expected, except for minor faults and associated breccias. None of these are likely to have significant adverse affects on mine stability. Flexibility related to waste emplacement in horizons other than the Topopah Spring Member was discussed in Section 6.3.1.3 (Postclosure rock characteristics). This evaluation examines emplacement only in the part of the densely welded, devitrified Topopah Spring Member that contains less than 15 to 20 percent lithophysae.

The primary area for locating the underground facility is shown as area 1 on Figure 6-24. Area 1 contains relatively few faults and rare fault breccias. Available data indicate that rock with acceptable characteristics is present in area 1, and could be present in area 2 and perhaps outside these areas (Sinnock and Fernandez, 1982; Mansure and Ortiz, 1984). On the basis of detailed surface mapping by Scott and Bonk (1984) of the possible repository expansion areas, area 2 has the greatest potential of containing rock with acceptable characteristics. The surface and subsurface geologic exploration of Yucca Mountain has concentrated on area 1 and the immediately surrounding area.

Analysis of a three-dimensional computer graphics model of Yucca Mountain (Nimick and Williams, 1984) indicates that area 1 contains approximately 890 hectares (2,200 acres), although minor faults and breccia and blocks rotated to steep dips may occupy some of the area. Approximately 749 hectares (1,850 acres) of area 1 are potentially usable on the basis of the disqualifying condition for erosion, which requires a 200-meter (656-foot) overburden. The acreage required for a repository that is designed to accomodate the equivalent of 70,000 metric tons of heavy metal (MTHM) is approximately 616 hectares (1,520 acres) (Mansure and Ortiz, 1984), suggesting that additional acreage outside area 1 may be needed for significant lateral flexibility in repository design. Area 2, a primary area for extending the underground facility from area 1, contains about 910 hectares (2,250 acres) and is similar to area 1 in fault density. Data for area 2 are limited to those obtained from surface mapping and extrapolation of drill hole data obtained mainly in and around area 1. If extension of the underground facility from area 1 is required to provide lateral flexibility, additional geologic characterization will be required to determine how much of this area is usable. Area 3 contains approximately 162 hectares (400 acres). Small portions of this area could violate the disqualifying condition requiring 200 meters (656 feet) of overburden. Area 4 contains approximately 607 hectares (1,500 acres) and also may have rock characteristics similar to the other areas, but fewer data exist for this area.

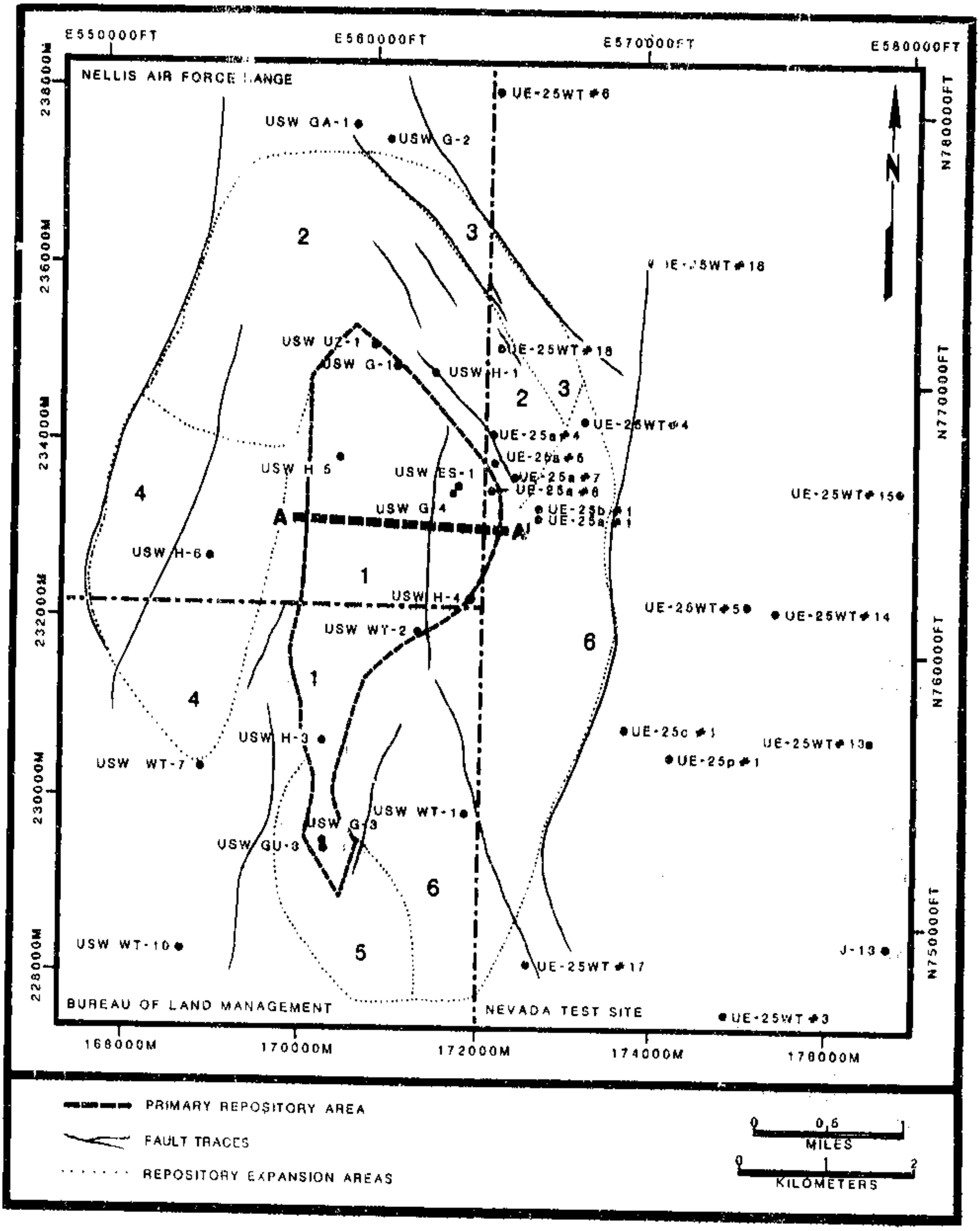

Figure 6-24. Potential repository expansion areas. Area 1 is the primary area for the underground facility. See text for detailed discussion of areas 1, 2, 3, 4, 5, and 6. Cross section A-A' is shown on Figure 6-25.

Portions of area 4 could also violate the disqualifying condition for 200 meters (656 feet) of overburden. Area 5 contains about 202 hectares (500 acres), and area 6 contains 1,072 hectares (2,650 acres). Area 6 has a very complex fault structure with steeply dipping faults, and part of area 6 may not meet the 200-meter (656-foot) overburden requirement.

The repository envelope is conservatively assumed to require 45 meters (148 feet) (Mansure and Ortiz, 1984). Basic requirements for the potential host rock are the presence of sufficient overburden and a sufficient thickness of suitable host rock to contain this envelope. Mansure and Ortiz (1984) show that the approximate thickness of the preferred host rock is on the order of 100 to 175 meters (330 to 575 feet) within area 1. The overburden at Yucca Mountain, as discussed in Section 6.3.1.5 (Erosion), is more than 300 meters (984 feet) over about 50 percent of area 1. In area 1, the thickness of the relatively lithophysae-free part of the densely welded Topopah Spring Member varies greatly; however, it is expected to be more than adequate for locating the underground facility.

To date, a value of 15 to 20 percent has been used to differentiate between the lower portion of the Topopah Spring Member, which is relatively free of lithophysae, and the upper portion, where lithophysae are more abundant. At low percentages, lithophysae have little effect. At high percentages lithophysae could change the thermomechanical properties of the rock, possibly to the point that minability and ground-support requirements may be affected. Although the preferred horizon is expected to have less than 15 to 20 percent lithophysae, this does not imply that the underground facility must be placed in host rock with less than 15 to 20 percent lithophysae, but only that host rock with lower lithophysae content may be preferable. The effect of lithophysae content on thermal properties of the host rock will be investigated during site characterization.

Figure 6-25 shows a cross section, A-A', through area 1 and the possible location of the underground facility. The preferred host rock is near the base of the unit marked Tpt. The basis for choosing this unit and other horizons considered as potential repository horizons are discussed in Chapter 2 and in Section 6.3.1.3 (Postclosure rock characteristics). In locating a preliminary horizon that represents the underground-facility volume, Mansure and Ortiz (1984) considered the dip and thickness of the host rock, the lithophysal content, and overburden requirements. The preliminary choice of horizon, shown in Figure 6-25, may change during site characterization. However, a single surface should be available that will satisfy all current design criteria. The strike and dip of the underground facility envelope (N 11° W, 5° E) will not result in grades too steep for waste-handling equipment. The strike and dip of the surface assumes a 5° east slope and a 1° north slope. Data gathered during site characterization will be used to determine whether the lateral extent of the host rock is sufficient to allow the position of the underground facility to be more nearly horizontal.

Conclusion

The potential host rock at Yucca Mountain is sufficiently thick to provide significant vertical flexibility in the placement of the underground facility. The primary repository area which has to date been the focus of

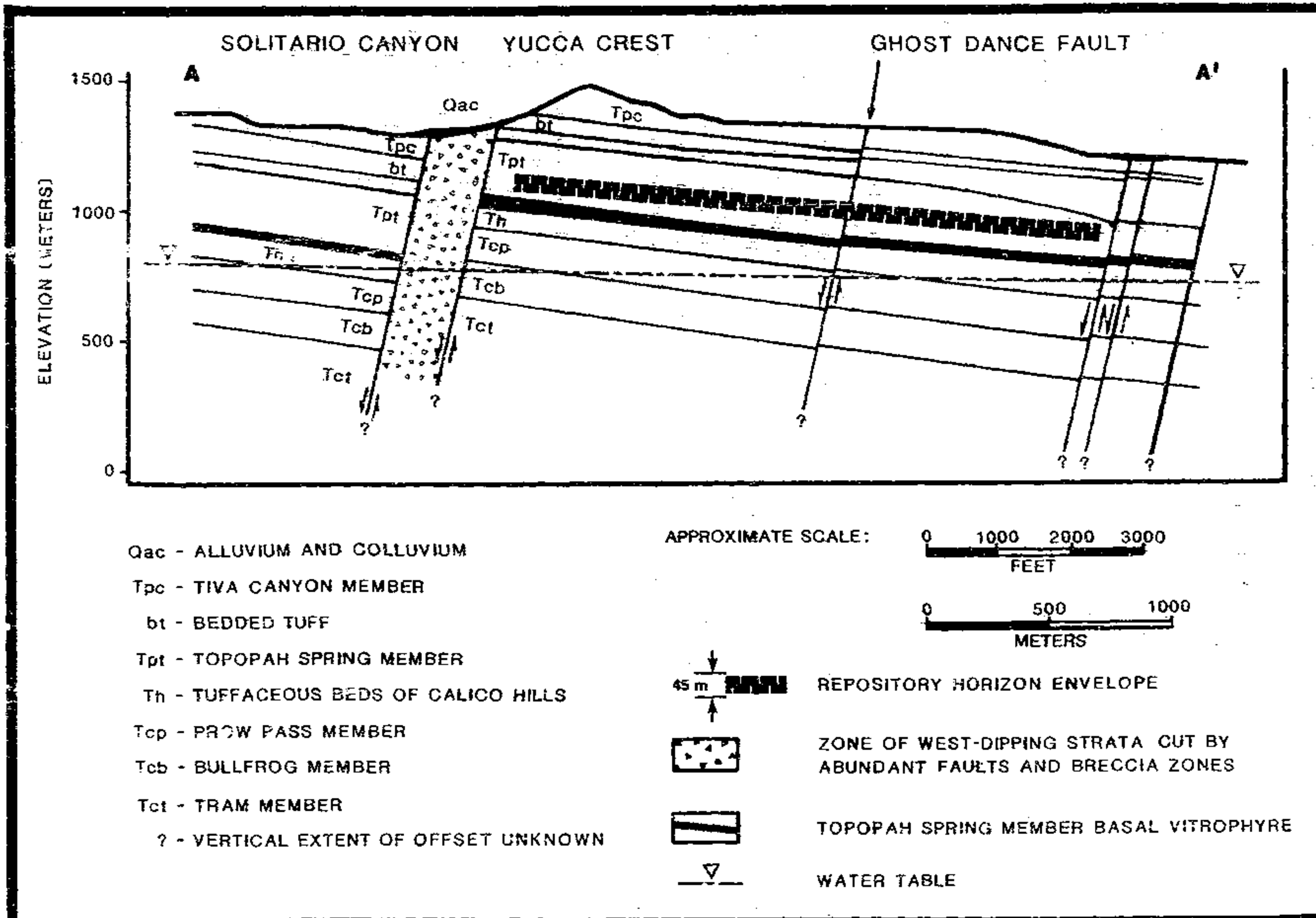

Figure 6-25. Approximately east-west cross section of primary repository area showing possible location of the underground repository envelope. For approximate location of cross section A-A', see map view in Figure 6-24. Modified from Mansure and Ortiz (1984).

exploration, provides limited lateral flexibility. Contiguous areas appear to have some rock that may be suitable, but additional exploration will be necessary to claim significant lateral flexibility. Therefore, the evidence indicates that this favorable condition is not present at Yucca Mountain.

(2) A host rock with characteristics that would require minimal or no artificial support for underground openings to ensure safe repository construction, operation, and closure.

Evaluation

Artificial support for underground openings is routinely used to ensure the stability of the openings and the safety of workers. The requirements for such artificial support are estimated by engineering judgment, experience gained from excavating rock types with similar characteristics, and calculations that simulate the expected rock behavior. The analyses and judgments used to support the conclusions of this section were developed from available core-property data, extrapolations based on rock-mass classification techniques, finite-element analyses of the mined openings, and minability assessments.

Techniques for classifying rock masses use compilations of existing underground-support practice, categorized according to parameters recognized as important, to estimate the required support for underground openings. These techniques are extremely useful in the preliminary design or feasibility stages of a project because they allow designers to make rational and generally conservative judgments about expected conditions. The rocks of the Topopah Spring Member have been assigned a range of rock-mass quality values based on available core data. Two widely used classification techniques were applied (Dravo Engineers, Inc., 1984): (1) the Council for Scientific and Industrial Research Classification System and (2) the Norges Geotekniske Institute Classification System. The rock-mass classifications derived from these two systems cover a range of values. A conservative approach to support design was taken by choosing conservative ranges for the input parameters. Given the assumption of a 6-meter (20-foot) span and the classification values, ground-support requirements can be estimated (Dravo Engineers, Inc., 1984) for the full range of expected conditions. The expected support requirements include (1) 2.5- to 3-meter (8- to 10-foot) long fully grouted rock bolts on a 1.5-meter (5-foot) grid spacing with steel wire mesh covering the rock surface for safety; (2) possibly shorter supplemental bolts added on a staggered grid spacing; and (3) in some instances 5 to 7 centimeters (2 to 3 inches) of shotcrete applied to rock surfaces.

There is no direct experience with excavation support requirements in the Topopah Spring Member at Yucca Mountain. However, these support requirements can be compared with experience in similar tuffs at the Nevada Test Site (NTS). The geologists and engineers familiar with tunneling and ground-support requirements for the welded Grouse Canyon Member at G-Tunnel at Rainier Mesa have suggested that the support requirements for the welded Topopah Spring Member at Yucca Mountain are likely to be similar (Ortego, 1985). The ground-support practice experience for the Grouse Canyon Member has been documented (Ortego, 1985), and consists of 2.5-meter (8-foot) epoxy grout-anchored rock bolts on a 1 by 1.3 meter (3 by 4 foot) spacing, supplemented by wire mesh. For the section of the tunnel that has been documented, Ortego (1985) noted that this support practice has proven to be adequate to date with no stability problems in the three years since tunnel construction.

The estimated ground-support requirements for a repository at Yucca Mountain are considered to be minimal in comparison with the ground support used in similar underground construction projects. For civil works such as tunnels, underground rail stations, and power plants, the support requirements for excavation stability are designed with safety factors that are several times larger than would be used for a mine or temporary excavation. Rock bolts and wire mesh are typically considered to be the minimal support for civil works projects, if for no reason other than worker safety. Major support requirements, such as steel sets or reinforced concrete, are not expected to be required at Yucca Mountain except perhaps in special areas, such as access ramps, shaft openings, and fault zones. The use of rock bolts, wire mesh and, in some instances, shotcrete sprayed on walls has the advantage of easy maintenance over an extended time, further ensuring the stability of mine openings through repository closure.

In estimating the support requirements for a repository, it is necessary to consider variations in room size as well as the stresses and displacements expected to result from the heat emitted by the waste. Variations in room sizes directly affect the stresses around openings. Heat-related stresses caused by waste emplacement have been predicted by numerical-analysis techniques. The preliminary analyses completed to date indicate that the stresses and displacements that are expected to result from the heat emitted by the waste would not lead to significant stability problems in the drifts (Johnstone et al., 1984). Confidence in these analyses is based on mining experience and field tests in similar devitrified, densely welded tuff in G-Tunnel at Rainier Mesa. A conservative design approach might, however, include additional rock bolts along the drift walls to offset the expected lateral expansion of the rock mass in response to the heat.

Long-term stability considerations for excavations in tuff must also include possible detrimental effects of the emplacement environment on the elements of the support system. For the emplacement drifts at Yucca Mountain two such considerations could be important: temperature effects on the rock bolt anchor system or shotcrete and corrosion effects on the rock bolts. The temperature field induced by the waste disposal containers could affect the stability of the epoxies that are used at the NTS to anchor rock bolts. There are several approaches that could be used to deal with this situation, should it be identified as a problem affecting drift stability. One approach would be to use an epoxy with a higher temperature service rating. Other approaches include the use of a full-length-anchored-friction-driven, or expanded bolts (such as Split Sets or Swellex) as well as cement-grouted bolts (grouted dowel or Perfo) and cement-cartridge-anchored bolts developed in Europe where epoxy-anchored bolts are not accepted as part of permanent support. Temperature effects on shotcrete lining, if any are used, would be manifested as strength reductions, particularly following a heating-and-cooling cycle. Kendorski et al. (1984) note that such strength reductions could exceed 25 percent at 205°C (400°F); they indicate, however, that proper mixture and composition can minimize these effects. Any loss of strength in the shotcrete can be compensated for by an equivalent proportional increase in thickness of the shotcrete.

Corrosion effects on the rock bolts are also a possible consideration in long-term suitability of the emplacement drifts at Yucca Mountain. A steel rock bolt, if subject to condensation or exposure to water vapor, could corrode. Isogalvanic coated and hot zinc-galvanized rock bolts are standard, off-the-shelf products designed to minimize corrosion. It is not clear that zinc-galvanized steel would prevent corrosion in the emplacement environment at Yucca Mountain; in fact, it could enhance corrison through cathodic behavior of the steel. However, other coatings such as nickel, cadmium, or epoxy would not be significantly more costly than zinc galvanizing and would perform better in inhibiting corrosion. Corrosion is not always detrimental to a bolt-type support system; the friction-anchored or expanded bolts become more effective as the steel corrodes because corrosion effectively increases the friction coefficient. Also, the cement-grouted bolt types are not very sensitive to corrosion, because their anchoring capacity is developed over the full length of the bolt and the grout protects the steel from corrosion.

Final decisions about elements to be used for the ground-support system will consider potential chemical interactions with the waste disposal container components and waste form. Additional thermal and chemical modeling and testing will be completed during site characterization to support final decisions on ground-support requirements.

Conclusion

Excavation experience at the NTS and numerical analyses of the stability of repository-sized openings suggest that an underground facility in the Topopah Spring Member at Yucca Mountain will require minimal artificial ground support for safe construction, operation, and closure. Therefore, the evidence indicates that this favorable condition is present at Yucca Mountain.

6.3.3.2.4 Potentially adverse conditions

(1) A host rock that is suitable for repository construction, operation, and closure, but is so thin or laterally restricted that little flexibility is available for selecting the depth, configuration, or location of an underground facility.

Evaluation

The requirements for host-rock thickness and lateral extent have been discussed under favorable condition 1 in this section and under favorable condition 1 of Section 6.3.1.3 (Postclosure rock characteristics). These discussions noted that most exploration has been limited to a portion of the Yucca Mountain site that is designated as area 1 in Figure 6-24. In most of the usable portion of area 1, the thickness of the low lithophysal portion of the potential host rock averages more than 3 times the value (45 meters or 148 feet) used as a conservative estimate of the envelope needed for the underground facility. Such a thickness is judged to provide significant flexibility in selecting the depth of the repository.

The analyses further indicate that area 1 has a usable area of approximately 749 hectares (1,850 acres). Present waste inventories and repository design concepts (Mansure and Ortiz, 1984) indicate that approximately 616 hectares (1,520 acres) is required for a repository. Comparison of these areas shows that the primary area contains slightly more usable area than that required for a repository, but if conditions are found to be unacceptable in some of this area, then flexibility in the lateral placement of the repository could be considered limited. Analysis of existing site data provides confidence that several contiguous areas (areas 2, 3, and 4 in Figure 6-24) could also contain suitable host rock. Area 2, the preferred expansion area, contains 910 hectares (2,250 acres). The suitability of these additional areas can be confirmed only by site characterization.

Conclusion

The host rock at Yucca Mountain is sufficiently thick to provide significant flexibility for selecting the depth of the underground facility. The primary area, which has been the focus of exploration, provides limited flexibility in lateral placement. Site characterization may expand the usable area, thereby allowing flexibility in lateral placement of the repository. However, considering only the primary area, this potentially adverse condition is present at Yucca Mountain.

(2) In situ characteristics and conditions that could require engineering measures beyond reasonably available technology in the construction of the shafts and underground facility.

Evaluation

Detailed ground-stability studies indicate that the Topopah Spring Member has no known in situ characteristics that cannot be successfully controlled by proven mining methods. The rock characteristics, as well as the design layout and development plan, are such that the underground facility can be developed by conventional mining methods (Dravo Engineers Inc., 1984). From the limited work done so far, it appears that mechanical mining could be used for repository construction in the Topopah Spring Member.

As discussed under favorable condition 2, it is likely that the repository drifts and underground openings can be adequately supported by conventional rock bolts and wire mesh. The discussions under potentially adverse condition 5 describe tunneling experience in similar devitrified, densely welded tuffs at Rainier Mesa that support this conclusion. The rock-bolt and wire-mesh support is minimal in comparison with the supports that are used in civil works projects such as highway tunnels or underground power stations. Steel, shotcrete, or both would be used at Yucca Mountain only if underground observations suggest that such support is necessary possibly, for example, at fault-zone intersections or drift intersections. The proposed ground support is within established technology (Dravo Engineers Inc., 1984). Shafts would be constructed by standard excavation techniques and lined with concrete (Hustrulid, 1984).

Most of the repository would be located more than 200 meters (656 feet) above the water table (Figure 6-26). Experience in tunnels at the Nevada Test Site (NTS) indicates that, if perched water is encountered, the flow will probably be small and should diminish rapidly. Drill holes in and near the site have not identified perched water at elevations above the base of the Topopah Spring Member (Section 6.3.1.1.3).

Conclusion

There are no indications that the in situ conditions and characteristics would require engineering measures beyond reasonably available technology. The shafts and underground facility can be constructed using proven technology and standard methods. Therefore, the evidence indicates that this potentially adverse condition is not present at Yucca Mountain.

(3) Geomechanical properties that could necessitate extensive maintenance of the underground openings during repository operation and closure.

Evaluation

The potential host rock is more than 200 meters (656 feet) (see Figure 6-19) below the ground surface. At this depth it would not be affected by weathering or surface water. A rectangular underground opening with an arch-shaped roof is expected to provide a stable opening in the Topopah Spring Member. Localized, minor spalling may occur near corners and on walls because of stress relief or the intersection of joints. Johnstone et al. (1984) noted that although modeling suggested that such fractures could develop in G-tunnel, none were, in fact, observed. As shown in Figure 6-25, most major faults occur outside the planned repository boundaries. As discussed under potentially adverse condition 5, the experience in a similar formation at Rainier Mesa suggests that minor fault zones at the Yucca Mountain site could be traversed by using standard mining and ground support technology. However, considerable data from site characterization are required to confirm this conclusion.

The shafts or access ramps of the repository will penetrate the upper members of the Paintbrush Tuff Formation. A study using the Council for Scientific and Industrial Research and the Norges Geotekniske Institute rock-mass classification systems indicated several alternative schemes for ground-support arrangements (Dravo Engineers, Inc., 1984); all of these arrangements use conventional techniques and equipment. The in situ conditions are such that excavation stability can be maintained with conventional rock bolts and wire mesh. This type of ground support requires limited maintenance, and dry conditions in the repository will reduce corrosion problems with the rock bolts or wire mesh and, in poor rock conditions, shotcrete. The use of an arched-roof opening would reduce stress and lends stability to the rock mass, further reducing support-maintenance requirements. Thus, stable conditions should continue through repository closure. Because of the long operating life of the repository (assumed to be

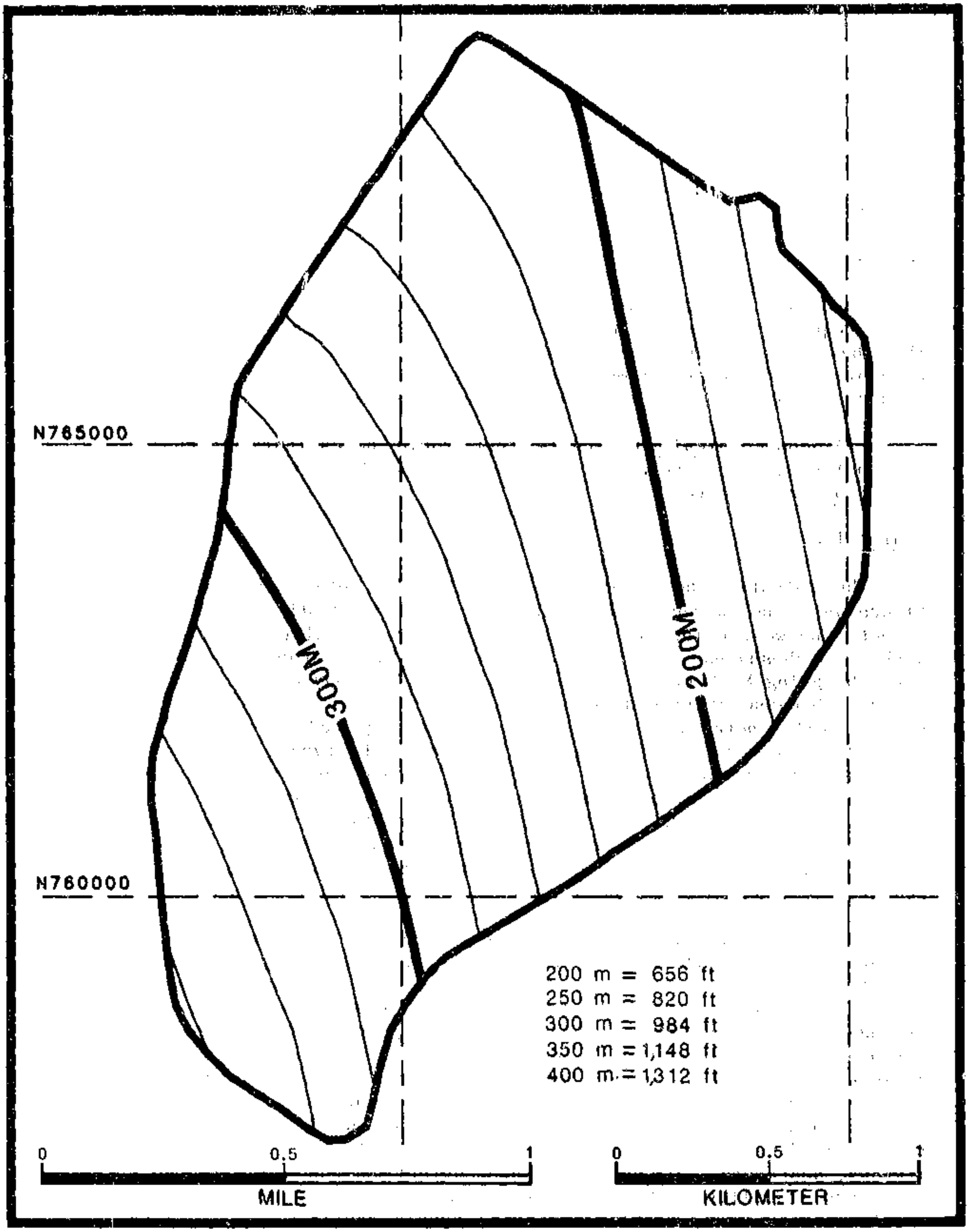

Figure 6-26. Total thickness of unsaturated zone from disturbed zone (located 50 meters (164 feet) below repository midplane) to water table. Modified from Sinnock et al. (1986).

90 years), some maintenance of underground openings will be required. The maintenance would be routine and well within the limits of existing practices and technology. The thermal stresses resulting from heating after waste emplacement are not expected to significantly affect the stability of the mined openings, although some very localized deformation might occur (Section 6.3.1.3).

Conclusion

The geomechanical behavior of the rocks at Yucca Mountain provides an inherently stable condition that will not require extensive maintenance to keep the underground openings in a serviceable condition for the operating life of the repository. Therefore, the evidence indicates that this potentially adverse condition is not present at Yucca Mountain.

(4) Potential for such phenomena as thermally induced fracturing, the hydration and dehydration of mineral components, or other physical, chemical, or radiation-related phenomena that could lead to safety hazards or difficulty in retrieval during repository operation.

Evaluation

Johnstone et al. (1984) have evaluated the stability of underground openings in the densely welded tuff of the Topopah Spring Member, and the response of the tuff to excavation and thermal effects. These preliminary studies included near-field mechanical and thermomechanical finite-element code calculations, rock-matrix property evaluation, and rock-mass classification. They considered the physical, thermal, and mechanical properties specific to the Topopah Spring Member; the existence of individual sets of fractures; and the expected in situ stress. The results were compared with the behavior of existing underground openings in similar devitrified, densely welded tuff at the NTS. The results indicate that (1) the mined openings are expected to remain stable through repository closure, and (2) the effects of thermally induced fracturing are very localized, being limited to the immediate vicinity of the waste emplacement holes and the periphery of the drifts.

Preliminary estimates predict a potential for rock-matrix fracturing in the immediate vicinity of the waste emplacement hole, but this fracturing should extend no more than 10 centimeters (4 inches) into the rock. The potential for block movement along minor joints or faults intersecting the hole wall is currently under investigation. No structural degradation has been observed in two small-diameter-heater tests conducted in tuff at G-Tunnel (Zimmerman, 1983). The effect of localized sloughing of the hole walls on waste retrievability could be minimized by using a steel liner in the waste emplacement hole.

No minerals present in significant quantities in the repository horizon are susceptible to thermally induced dehydration, hydration, or radiation-related phenomena. Bish et al. (1984) summarize the distribution of minerals in the tuffs at Yucca Mountain and state that about 98 percent of the proposed repository host rock is made up of alkali feldspar, quartz, tridymite, and cristobalite, which are not subject to thermally induced dehydration or hydration. The proposed repository horizon contains 1 percent or less of smectite (Bish et al., 1984) and is generally not zeolitized (Bish et al., 1982). Thus, there is little potential for the hydration or dehydration of minerals that could affect the safety of repository operation or cause problems with waste retrieval. Cristobalite exhibits an alpha-to-beta phase transition between 235 and 260°C (455 and 500°F) in confined tests (Lappin, 1980a), which is reflected by a slight increase in the thermal expansion coefficient. Because of the transformation temperature this transition would be expected only in the very near-field of the waste disposal container. The thermomechanical studies use thermal expansion coefficients that account for this behavior; they predict no additional rock fracture beyond the 10 centimeters (4 inches) reported above.

Conclusion

The welded tuff at Yucca Mountain is a physically and chemically stable rock that will be little affected by repository conditions. About 98 percent of the potential host rock consists of alkali feldspar, quartz, tridymite, and cristobalite, all of which are nonhydrous minerals. Currently, the rock is fractured, and any additional thermally induced fracturing will be minor and will not create a safety hazard or produce difficulty in waste retrieval, should retrieval be necessary. Therefore, the evidence indicates that this potentially adverse condition is not present at Yucca Mountain.

(5) Existing faults, shear zones, pressurized brine pockets, dissolution effects, or other stratigraphic or structural features that could compromise the safety of repository personnel because of water inflow or construction problems.

Evaluation

Artificial support for underground openings is routinely used to ensure the stability of the openings and the safety of workers. The requirements for such artificial support are estimated by engineering judgment, experience gained from excavating rock types with similar characteristics, and calculations that simulate the expected rock behavior. The analyses and judgments used to support the conclusions of this section were developed from available core-property data, extrapolations based on rock-mass classification schemes, finite-element analyses of the mined openings, and minability assessments.

The hydrogeologic conditions of the region and site are described in Section 6.3.1.1. Data on water levels in drill holes within and near the site are shown on Figure 6-3. Naturally occurring perched water of any significance have not been identified in existing drill holes, and no pressurized water zones have been encountered. Only very small amounts of water are expected to seep into excavated drifts by gravity drainage.

Even though faults and associated shear zones exist at Yucca Mountain, the preferred repository area is expected to be minable with standard equipment (Dravo Engineers, Inc., 1984) (see favorable condition 2). Rock with similar mechanical properties has been excavated at the G-Tunnel complex in Rainier Mesa using comparable methods of excavation and ground control. Tibbs (1985) has documented tunneling experience in the welded Grouse Canyon Member at G-Tunnel. A nearly vertical fault with at least 1 meter (3 feet) of vertical displacement was encountered during tunneling activities in the welded Grouse Canyon Member in G-Tunnel. No comments were noted by the mining inspector in his daily log; the lack of comments indicates that tunneling conditions had not varied appreciably. The fault zone was not noted until the tunnel had advanced about 6 meters (18 feet) beyond the fault. The fault brought welded and nonwelded tuff together along a nearly vertical contact; no water influx was noted. The inspection record shows that the area of the tunnel with the fault was initially mined on November 19, 1981. Preliminary 2.5-meter (8-foot) rock bolts were installed in the faulted area on November 20, 1981, and then on February 16, 1982, roughly 3 months later, 5-meter (16-foot) resin-anchored hardening rock bolts were installed on a 1.3 by 1.3 meter (4 by 4 foot) pattern across the back in the area adjacent to the fault. There was no record that the faulted area produced ground-support problems, and no special bolting was installed in the area of the fault. The conclusion drawn by Tibbs (1985) is that the crossing of the nearly vertical fault with at least 1 meter (3 feet) of vertical displacement did not result in the need for any special ground support in excess of the standard methods used in the drift where no faulting occurred.

Because there may be a need to expand the repository boundaries laterally to increase flexibility (see favorable condition 1), Dravo Engineers, Inc. (1984) has evaluated the potential for mining through the faults and fault zones that bound parts of the primary repository area at Yucca Mountain. Limited data show that the boundaries of the primary repository area (area 1) could be traversed using standard mining and support technology. However, considerable site characterization is required to confirm this analysis. According to Dravo Engineers, Inc. (1984) and confirmed by the Rainier Mesa tunneling experience described above, drifts across the minor fault zones found within the primary area can be excavated without using unusual or unsafe construction practices. Increased ground support could be provided in these areas, or in any areas with less stable rock, to further reduce any potential hazard to workers.

Potential Hazards to Excavation Workers

To evaluate the potential hazards to excavation workers at Yucca Mountain, excavation experience in the welded and nonwelded tuffs at the NTS that have been used for weapons-effect testing has been examined. The safety records show that such excavations can be carried out with minimum adverse effects on worker safety. The safety record can be quantified through the use of incidence rates for worker injury that were associated with time away from work. To assess the relative level of safety for tunneling operations at the NTS, the incidence rates for NTS operations can be compared to injury incidence rates for similar mining operations. Such a comparison is presented in Figure 6-27. The industry category that is most similar to excavation conditions in the tuffs at NTS is the category of hard-rock metal mining. The data presented in Figure 6-27 are based upon industry average data compiled by the National Safety Council and data for NTS operations compiled by Reynolds Electric and Engineering Co., the U.S. Department of Energy contractor for excavation operations. The data presented in Figure 6-27 clearly indicate a significantly better safety record for NTS tunneling operations than is typical of industry practice. While the industry average incidence rate is lower now than it was 20 years ago by a

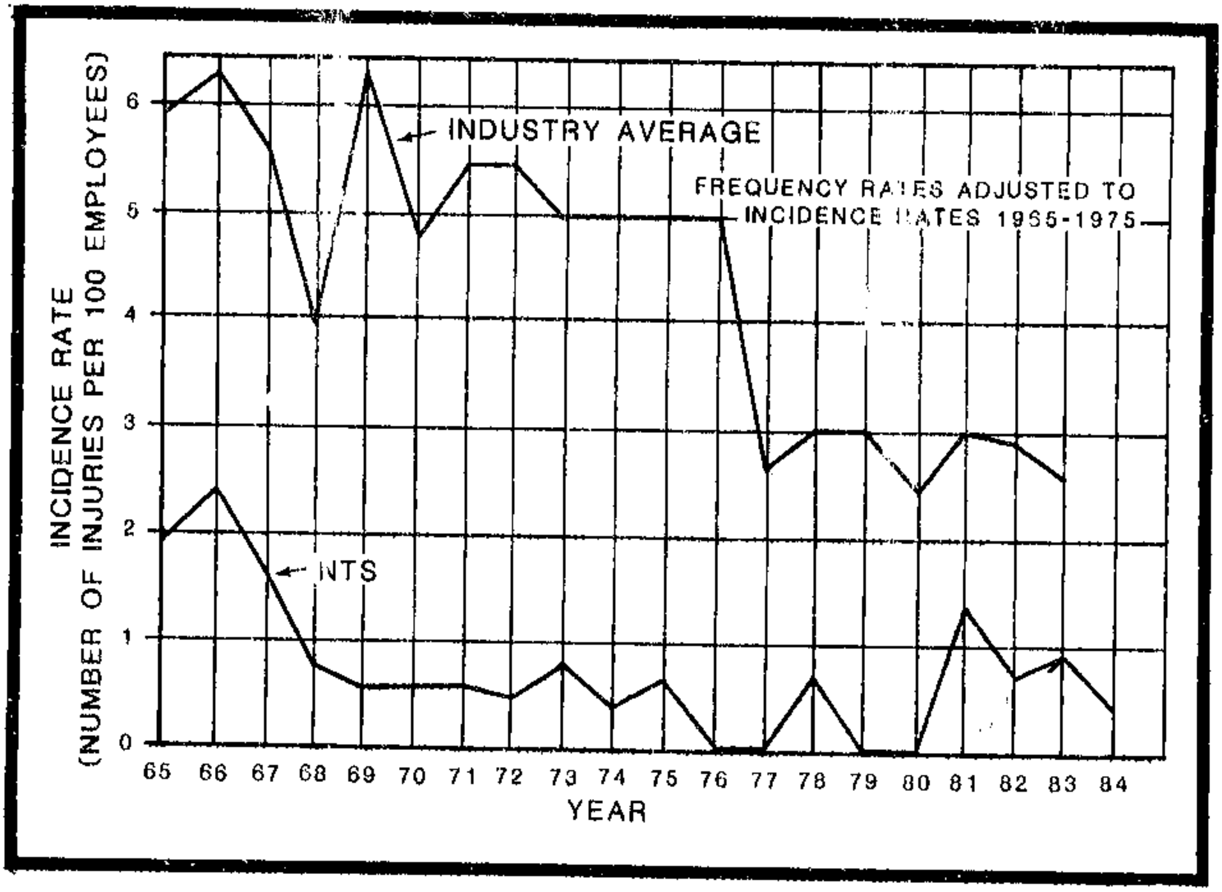

Figure 6-27. Incidence rate of injuries in tunneling operations at the Nevada Test Site compared to industry averages for hard-rock metal mining. Modified from Schueler (1985).

factor of about 2, NTS operational safety record is still lower than the industry average by a factor of about 3. For the past 10 years, NTS practice which heavily emphasizes worker safety, has resulted in an average injury-incidence rate of less than 1 injury per year per 100 employees.

There are several possible reasons for the difference between industry average and observed NTS incidence rates. One possible reason is that safety standards and enforcement practice at the NTS are probably more stringent than is typical of the mining industry. NTS practice incorporates the concepts of Mine Safety and Health Administration, California Department of Mines safety orders, and DOE Order 5480.1 on safety orders (DOE, 1981) and uses the most stringent governing standards from these regulations. Another possible reason is that whereas standard mining practice must be production oriented to be economical, the tunnels at the NTS are designed and constructed for long-term serviceability and stability. Yet another possible reason is that mining operations typically deal with potentially unstable ground conditions because of the emplacement mode of the minerals being excavated. It is not possible to determine from the data in Figure 6-27 the relative importance of these three possible reasons for the difference in safety at the NTS as compared to the industry average. However, it is clear that all or any of these reasons provide support for the conclusion that tunneling in the various tuff formations at NTS, following existing NTS practice, is significantly safer than hard-rock metal mining in the industry as a whole.

Specific excavation experience in G-Tunnel at the NTS is of interest because part of the G-Tunnel experience involves a welded tuff, the Grouse Canyon Member. Engineers and geologists familiar with excavation in the welded Grouse Canyon Member have expressed the opinion that the ground support that will be required in the Topopah Spring Member at Yucca Mountain is likely to be similar to that required in the welded Grouse Canyon Member (Ortego, 1985). Accident experience at G- and N-Tunnels at the NTS for the period between 1975 and 1985 is summarized by Dunnam (1985). Dunnam states that none of the accidents identified in a search of tunnel records could be considered to be caused by unstable ground, faulting, or other such geologically related conditions. He further observes that this is consistent with his recollections of the period between approximately 1965 and 1985 for NTS operational experience. The one accident that involved the falling of a piece of rock was the result of an oversight in barring down loose rock prior to support installation. The accident report in question indicates that this accident probably would not have occurred if the correct NTS mining practice had been followed. It is important to note that the reported activities in the welded Grouse Canyon Member involved tunneling through a fault zone with 1 meter (3 feet) of observed displacement (Tibbs, 1985).

Conclusion

Faults and shear zones that could compromise the safety of repository personnel because of construction problems or water inflow are not expected in the primary repository area at Yucca Mountain. The design and layout of the underground facility will minimize contact with portions of the host rock where minor faults and shear zones are identified. There is no indication that pressurized brine pockets, evidence of dissolution, or significant accumulations of water or toxic gases are present in the repository horizon.

Hence, no other conditions that could compromise the safety of repository personnel are expected. Safety records for excavation in tuffs at the NTS show that such work has been carried out for more than 20 years with an incidence of injuries that is well below comparable industry averages. Therefore, the evidence indicates that this potentially adverse condition is not present at Yucca Mountain.

6.3.3.2.5 Disqualifying condition

> The site shall be disqualified if the rock characteristics are such that the activities associated with repository construction, operation, or closure are predicted to cause significant risk to the health and safety of personnel, taking into account mitigating measures that use reasonably available technology.

Evaluation

The current data base for the geoengineering properties of the potential host rock consists of the results of laboratory tests on core samples from Yucca Mountain and Rainier Mesa (Lappin, 1980a,b; Lappin et al., 1982; Price et al., 1982a,b; Price, 1983). Rainier Mesa and Yucca Mountain are both composed of layered volcanic rocks, and recent measurements on core samples from densely welded tuffs from both sites indicate that the mechanical properties of the rock matrix are similar; however, it should be noted that a large part of G-Tunnel contains nonwelded tuffs. Excavations in G-Tunnel beneath Rainier Mesa and planned excavations at Yucca Mountain are similar with regard to overburden loadings, opening dimensions, and excavation methods. Because of these similarities, field observations, tests and experience in G-Tunnel can be used to support decisions related to the safe construction, operation, and closure of a repository at Yucca Mountain.

The in situ stress state affects the stability of openings. Stress measurements from rock units below the water table at Yucca Mountain were used to calculate ratios of vertical stress to the minimum horizontal stress. The results show ratios of up to 3.1 (Healy et al., 1984), with a mean of 2.2 for 6 measurements and a standard deviation of 0.4. No reliable stress measurements have been made on the unsaturated zone or on the potential host rock. The stress ratios for tuffs in G-Tunnel have a mean of 2.7 and a standard deviation of 1.3 for 67 measurements (Tyler and Vollendorf, 1975; Ellis and Ege, 1976; Warpinski et al., 1978). G-Tunnel is generally supported only with rock bolts and wire mesh. In the more than 10 years of tunnel operation, the stresses have not resulted in problems in opening stability, even when augmented by severe ground motion from nuclear tests in the tunnel.

The selection of densely welded portions of the Topopah Spring Member as the potential repository host rock was based in part on the average thermal and mechanical properties defined for each of the four horizons that were considered (Tillerson and Nimick, 1984). Available data came from approximately 75 thermal conductivity tests, 95 thermal expansion tests, 35 mineralogic and petrologic analyses, 60 mechanical tests on jointed rock samples, and 120 tests of unconfined and 50 pressure-dependent mechanical properties tests. The average values for the thermal and mechanical properties of the rock in the Topopah Spring Member are given in Table 6-40.

Johnstone et al. (1984) used nonlinear, finite-element analyses of thermomechanical stresses, standard rock-mass classification systems, and linear calculations for mine design and pillar sizing to evaluate the expected stability of openings. Their preliminary results indicate that existing mining technology can be used to develop stable underground openings that will allow repository operations to be safely carried out from construction through closure. The experience gained in G-Tunnel at Rainier Mesa on the Nevada Test Site (NTS) supports this conclusion; it also indicates that only minimal support for the openings (i.e., rock bolts and wire mesh) would be required. Minability assessments (Tillerson and Nimick, 1984), also supported by G-Tunnel experience, indicate that controlled blasting can be successfully used to excavate openings in the densely welded tuff.

The only other significant physical or chemical phenomena known to be associated with rock characteristics are related to ventilation-system design and worker safety. The temperature increases resulting from the emplaced waste are important in designing ventilation systems and in selecting the standoff distance between the drift and the emplaced waste. Excavations at the NTS show that explosive or other hazardous gases are not to be expected. The ventilation system primarily controls dust. Hazards associated with the dust will be mitigated by supplying adequate flow volumes and filters to meet safety requirements. Similarly, estimates of low-level radiation from the naturally occurring radon released during rock excavation will be used in establishing ventilation requirements. Techniques already implemented in the uranium mining industry will be considered. The proper design and operation of a ventilation system based on current technology should readily mitigate dust and radiation concerns.

Tunnel excavation experience in the welded and nonwelded tuffs at the NTS has shown that such excavations can be carried out with minimum adverse effects on the health and safety of workers. The NTS safety record was quantified and compared to safety records in a similar industry (hard-rock metal mining) in Section 6.3.3.2.4. The incidence rate of injuries at the NTS is about a factor of 3 lower than the industry average for hard-rock metal mining (Schueler, 1985).

<u>Conclusion</u>

Applicable laboratory data, field experience with similar excavations, and thermomechanical stress calculations show that activities associated with the construction, operation, or closure of a repository at Yucca Mountain will not cause significant risk to the health and safety of personnel. Therefore, on the basis of the above evaluation, the evidence does not support a finding that the site is disqualified (level 1).

Table 6-40. Average thermal and mechanical properties of the Topopah Spring Member[a]

Property	Value
Thermal conductivity (saturated), W/m-°C	1.8 ± 0.4
Thermal conductivity (dry), W/m-°C	1.6 ± 0.4
Predehydration linear expansion coefficient, 10^{-6}/°C	10.7 ± 1.7 (to 200°C)
Transition-dehydration linear expansion coefficient, 10^{-6}/°C	31.8 (to 300°C)
Postdehydration linear expansion coefficient, 10^{-6}/°C	15.5 ± 3.8 (to 400°C)
Young's modulus, GPa	26.7 ± 7.7
Poisson's ratio 0.14 ± 0.05	
Unconfined compressive strength, MPa	95.9 ± 35.0
Matrix cohesion, MPa	28.5
Angle of internal friction, degrees	26.0
Matrix tensile strength, MPa	12.8 ± 3.5
Joint cohesion, MPa	1
Coefficient of friction for initiation of sliding on joints	0.8

[a]Data from Tillerson and Nimick (1984).

6.3.3.2.6 Evaluation and conclusion for the qualifying condition on the preclosure rock characteristics guideline

Evaluation

The lateral and vertical extent of the potential repository host rock at Yucca Mountain provides reasonable flexibility for the vertical placement of the repository, and somewhat limited lateral flexibility for repository placement. Current repository design concepts require 616 hectares (1,520 acres), and the primary repository area contains 890 hectares (2,200 acres) of which approximately 749 hectares (1,850 acres) are considered potentially usable. It may therefore be necessary to extend the repository outside the primary area of Yucca Mountain. Current information indicates that standard mining and support technology would be adequate for this expansion.

Previous experience and presently available data (see favorable condition 2) suggest that artificial-support requirements for the proposed excavation would be minimal and would enable work to be performed without undue hazard to personnel and at reasonable cost throughout the entire repository operations cycle, including retrieval, should retrieval be necessary. At present, there is no evidence that the geomechanical properties of the Topopah Spring Member will respond to waste-emitted heat in any way that would lead to hazardous conditions in the repository that could affect worker safety or preclude waste retrievability.

Conclusion

The lateral extent of the potential host rock is adequate, but it has not been demonstrated to provide significant lateral flexibility for locating the underground facility. There is reasonable flexibility for the vertical positioning. Furthermore, information obtained to date suggests that lateral flexibility is likely to be demonstrated during site characterization. Preliminary exploration activities have not identified any rock characteristics that would cause undue hazards to personnel. Repository siting, construction, operation, and closure can be carried out with reasonably available technology. Therefore, on the basis of the above evaluation, the evidence does not support a finding that the site is not likely to meet the qualifying condition for preclosure rock characteristics (level 3).

6.3.3.2.7 Plans for site characterization

Site-characterization activities will supplement the existing data base, both through exploratory borings, access to the proposed host rock, and additional laboratory tests. Construction phase tests will provide in situ stress data and shaft convergence data that will be used for design and layout of underground facilities. Large-scale tests performed in the potential repository host rock during the in situ phase of exploratory shaft testing will supplement the data base by providing information on the in situ rock conditions as well as effects, such as fracturing caused by stress and temperature. A large-scale heater test is planned to confirm the behavior of the host rock in the very near field where the highest temperatures and stresses will be induced.

6.3.3.3 Hydrology (10 CFR 960.5-2-10)

6.3.3.3.1 Introduction

The qualifying condition for this guideline is as follows:

The site shall be located such that the geohydrologic setting of the site will (1) be compatible with those activities required for repository construction, operation, and closure; (2) not compromise the intended functions of the shaft liners and seals; and (3) permit the requirements specified in Section 960.5-1(a)(3) to be met.

The preclosure hydrology technical guideline is concerned with surface and subsurface water that could affect repository surface and underground facilities during construction, operation, and closure. Surface waters have the potential for flooding the underground facility, access ramps, and shafts; they could also affect the ease and cost of constructing and operating the surface and support facilities, including transportation access routes.

Water will be required for the construction, operation, closure, and decommissioning of the repository. The subsurface hydrologic conditions will have a bearing on the cost and safety of construction, operation, closure, and decommissioning. Subsurface water must not compromise the intended functions of the shaft liners and seals. This guideline relies on technical information similar to that supporting the guideline on geohydrology (Section 6.3.1.1).

This guideline consists of three favorable conditions, one potentially adverse condition, one disqualifying condition, and one qualifying condition. The evaluations reported below are summarized in Table 6-41 for all conditions except the disqualifying condition.

6.3.3.3.2 Data relevant to the evaluation

Water-table altitudes at wells near the potential repository site range from about 730 meters (2,400 feet) along the eastern edge to about 780 meters (2,600 feet) near the northwestern edge, along the ridge crest of Yucca Mountain (Robison, 1984). Hydrologic test holes near Yucca Mountain have been tested at yields ranging from about 6×10^{-4} to 4×10^{-2} cubic meters per second (10 to 600 gallons per minute) (Waddell et al., 1984). Well J-13 has intermittently produced more than 0.04 cubic meters per second (600 gallons per minute) between 1962 and 1983 with no effect on water-table altitude (Thordarson, 1983).

Competing requirements for ground water have been considered. Surface water has not been considered for repository or domestic use, because it is not generally available in this arid region. Well J-13 and the proposed location of repository surface facilities are at the Nevada Test Site. If Yucca Mountain is selected for repository development, a permanent land withdrawal will be necessary, and a reservation of water rights is explicit in the withdrawal (Section 6.2.1.3). Estimates of water withdrawals and

Table 6-41. Summary of analyses for Section 6.3.3.3; hydrology (10 CFR 960.5-2-10)

Condition	Department of Energy (DOE) finding
FAVORABLE CONDITIONS	
(1) Absence of aquifers between the host rock and the land surface.	The evidence indicates that this favorable condition is present at Yucca Mountain: the host rock is above the water table.
(2) Absence of surface-water systems that could potentially cause flooding of the repository.	The evidence indicates that this favorable condition is not present at Yucca Mountain: there are no perennial stream channels that could potentially flood the repository; however, rare extreme storms could result in flooding of the repository surface facility and access routes due to sheet flow.
(3) Availability of the water required for repository construction, operation, and closure.	The evidence indicates that this favorable condition is present at Yucca Mountain: sufficient ground water is expected to be available from nearby wells.
POTENTIALLY ADVERSE CONDITION	
Ground-water conditions that could require complex engineering measures that are beyond reasonably available technology for repository construction, operation, and closure.	The evidence indicates that this potentially adverse condition is not present at Yucca Mountain: the potential repository is above the water table and no significant amounts of ground water are expected; shafts and boreholes are expected to be adequately sealed with available technology.

Table 6-41. Summary of analyses for Section 6.3.3.3; hydrology (10 CFR 960.5-2-10) (continued)

Condition	Department of Energy (DOE) finding
QUALIFYING CONDITION	
The site shall be located such that the geohydrologic setting of the site will (1) be compatible with those activities required for repository construction, operation, and closure; (2) not compromise the intended functions of the shaft liners and seals; and (3) permit the requirements specified in Section 960.5-1(a)(3) to be met.	Available evidence does not support the finding that the site is not likely to meet the qualifying condition (level 3): host rock is above the water table; wells are expected to provide adequate water supply; there are no surface-water systems that could flood the repository or compromise shaft liners and seals; and transient runoff will be adequately handled with routine drainage control measures.

consumption by counties and hydrographic regions are included in a series of water planning reports by the Office of the State Engineer (1971, 1974). These estimates provide a basis for projecting future water requirements in Nevada. Water requirements for the construction, operation, closure, and decommissioning of the repository have been estimated on the basis of the preliminary conceptual designs. The average annual consumption of water for a 32-year period of repository construction and operation is estimated to be about 432,000 cubic meters (350 acre-feet) (Morales, 1985)

Squires and Young (1984) have made predictions for 100-year, 500-year, and regional maximum floods; these predictions, describe in Section 6.3.3.1, have been used in estimating the potential for flooding surface and underground facilities. Fernandez and Freshley (1984) evaluated the need for shaft liners and seals. Data on ground-water conditions that are routinely encountered and managed with available technology in mines is given by Loofbourow (1973).

Assumptions and data uncertainties

The altitude and configuration of the water table in the Yucca Mountain area are known relatively well because numerous boreholes penetrate the water table, and water levels have been measured precisely (Robison, 1984). However, few moisture-content values or other hydraulic properties have been measured in the unsaturated zone, whose characteristics are therefore less certain. There is uncertainty about the moisture distribution in the unsaturated zone, which could affect sealing concepts. The occurrence of perched-water zones at Yucca Mountain was considered in the sealing-concepts study (Fernandez and Freshley, 1984), but as explained in Section 6.3.1.1, its likelihood is very low.

Uncertainty regarding flooding potential is discussed in Section 6.3.3.1 (Surface characteristics). The analysis of surface-water systems (favorable condition 2) is covered in Section 6.3.3.1.

Estimates of water use during repository construction, operation, closure, and decommissioning are conservative. The effects of increased ground-water withdrawal on regional ground-water supplies have some uncertainty but are considered negligible. Even if the estimates for repository activities were doubled, the effect on the available water at Yucca Mountain would be negligible.

6.3.3.3.3 Favorable conditions

(1) Absence of aquifers between the host rock and the land surface.

Evaluation

There are no aquifers between the host rock and the land surface. The potential repository horizon is located in the unsaturated zone, 200 to 400 meters (650 to 1,300 feet) above the water table (Figure 6-2) (Robison, 1984). Even if the basal vitrophyre of the Topopah Spring Member were included in the repository, the water table still would be over 150 meters (330 feet) below the repository.

There is the potential for perched-water zones between the host rock and the land surface. However, it is unlikely that large perched zones occur because they have not been encountered in drill holes to date (over 30 drill holes have been completed within approximately 10 kilometers (6 miles) of the site).

Conclusion

The potential host rock is above the water table at Yucca Mountain and there are no aquifers between it and the overlying land surface. Therefore, the evidence indicates that this favorable condition is present at Yucca Mountain.

(2) Absence of surface-water systems that could potentially cause flooding of the repository.

Evaluation

The reference surface facility location is located entirely outside of the main-channel flood zones predicted for the 100-year flood in the Fortymile Wash drainage system (Squires and Young, 1984). Some portions of the surface facilities may be in areas that could be affected by the 500-year and regional maximum floods predicted by Squires and Young (1984). A study will be conducted during site characterization to determine the probable maximum flood (PMF) in the vicinity of the site.

The washes on, and draining away from, Yucca Mountain have generally steep slopes and during extreme precipitation events are capable of moving large volumes of water and debris including boulders. Structures and shafts will be located to avoid such large volumes of water and debris. In addition, standard drainage-control measures, such as channel lining and flow diversion, will be used where needed. For additional information, see Section 6.3.3.1.

Conclusion

Surface-water drainage through the arroyo systems feeding Fortymile Wash presents a potential for localized flash flooding and sheet flow during extreme storm events. Some portion of the surface facilities might be located in areas that could be affected by the probable maximum flood (PMF). Therefore, the evidence indicates that this favorable condition is not present at Yucca Mountain.

(3) Availability of the water required for repository construction, operation, and closure.

Evaluation

Estimates of water needed for repository construction and operation are given in Chapter 5. The average annual consumption for a 32-year period of construction and operation is estimated to be approximately 432,000 cubic meters (350 acre-feet) (Morales, 1985).

Hydrologic test holes near Yucca Mountain have been tested at yields ranging from about 6×10^{-4} to 4×10^{-2} cubic meters per second (10 to 600 gallons per minute) (Waddell et al., 1984). Well J-13 (Figure 6-2), which supplies some local water needs in the southwestern part of the Nevada Test Site has yielded as much as 0.04 cubic meters per second (600 gallons per minute) during pumping tests (Thordarson, 1983). Pumping has lowered the water level in the well only slightly, and effects on the regional ground-water system are probably negligible. The static water level was 728.8 meters (2,391 feet) shortly after the well was drilled in 1962; 18 years later, after long periods of intermittent pumping, the water level was essentially the same, 728.9 meters (2,391 feet) (Thordarson, 1983). The excellent production capabilities of Well J-13, combined with the equally good production from the deep regional aquifers under Yucca Mountain (Section 3.3), suggest that sufficient quantities of water can be produced with negligible lowering of the regional ground-water table. Estimates of other ground-water withdrawals in the region are included in reports of the Office of the State Engineer (1971 to 1974).

Conclusion

The ground-water supplies available from nearby wells will be sufficient to satisfy all requirements during the repository life cycle. Therefore, the evidence indicates that this favorable condition is present at Yucca Mountain.

6.3.3.3.4 Potentially adverse condition

Ground-water conditions that could require complex engineering measures that are beyond reasonably available technology for repository construction, operation, and closure.

Evaluation

Because the potential repository at Yucca Mountain would be located entirely within the unsaturated zone, no significant amounts of ground water will be encountered in the underground workings. Furthermore, tunnels in tuffs below Rainier Mesa at the Nevada Test Site are in an area of greater surface recharge and probably of greater moisture flux in the unsaturated zone than in the proposed repository horizon at Yucca Mountain. Inasmuch as extraordinary mining techniques have not been required at Rainier Mesa, none are expected to be needed at Yucca Mountain.

Substantially more severe ground-water conditions than those expected at Yucca Mountain are routinely encountered and dealt with in mines (Loofbourow, 1973); therefore, no engineering measures beyond those presently available are likely to be needed. This expectation is based largely on experience.

A study has been made to determine the effects of the unsaturated zone environment on shaft liners and seals. The sealing concepts developed to date are based on data obtained from boreholes. Preliminary calculations of seal performance were based on a conceptual understanding of the hydrogeology and supplemented by information from comparable tuff sequences at Rainier Mesa. Should sealing be required, relatively simple and straightforward solutions are proposed (Fernandez and Freshley, 1984). These include filling drifts and ramps with coarse-grained material, using drains where water seeps are encountered, and using grout if more massive flows occur. For sealing borehole USW G-4 (the principal borehole for the exploratory shaft), which penetrates the proposed repository horizon, the use of zeolite fill, slurry, or grout seals is proposed. The same treatment would be used for nearby boreholes that penetrate the repository horizon or the underlying tuffaceous beds of Calico Hills.

Conclusion

The proposed repository at Yucca Mountain is entirely within the unsaturated zone, and no significant amounts of ground water are likely to be encountered in the underground workings. The ground-water conditions at Yucca Mountain will not require complex engineering measures. Sealing of shafts and boreholes is not expected to present any problems. Therefore, the evidence indicates that this potentially adverse condition is not present at Yucca Mountain.

6.3.3.3.5 Disqualifying condition

A site shall be disqualified if, based on expected ground-water conditions, it is likely that engineering measures that are beyond reasonably available technology will be required for exploratory shaft construction or for repository construction, operation, or closure.

Evaluation

The repository at Yucca Mountain would be located 200 to 400 meters (650 to 1,300 feet) above the water table. The evidence collected to date from boreholes indicates a very low potential for encountering significant quantities of perched water during exploratory shaft or repository construction. Because the potential host rock is highly fractured, perched-water zones are not likely to be extensive, and if encountered, the water would quickly drain away. Mines are routinely excavated in environments that are much more severe than those expected at Yucca Mountain. Current engineering and technology are more than adequate to handle the hydrologic conditions that are likely to be encountered during the construction of the exploratory shaft or during repository construction, operation, and closure.

Conclusion

It is highly unlikely that significant amounts of ground water will be encountered during the construction of the exploratory shaft and during repository construction, operation, and closure. Currently available engineering measures are considered more than adequate to guarantee that no disruption of construction and operation will occur because of ground-water conditions at Yucca Mountain. Therefore, evidence does not support a finding that the site is disqualified (level 1).

6.3.3.3.6 Evaluation and conclusion for the qualifying condition on the preclosure hydrology guideline

Evaluation

The known conditions at Yucca Mountain indicate a benign hydrologic situation with respect to construction, operation, and closure of a repository: the potential host rock is above the water table; nearby wells will provide adequate water for construction, operation, and closure; and no engineering measures beyond those presently available will be required by ground-water conditions. Because of the unsaturated conditions, sealing of drifts is probably unnecessary, and routine sealing methods are expected to be adequate for sealing shafts and boreholes. Although portions of the surface facilities may be located on a 500-year floodplain or within the region affected by the probable maximum flood, existing technology and standard drainage control measures are likely to provide adequate protection. Surface or underground facilities are unlikely to be inundated because of the small volume and transient nature of the sheet flow and flash floods that are typical of arid climatic settings like Yucca Mountain.

Conclusion

The unsaturated zone at Yucca Mountain appears to provide a favorable hydrologic environment for underground facilities, offering no currently recognized conditions that would require complex technology or costly engineering measures. Reasonable drainage control measures will provide adequate protection against sheet flow and flash flooding, and adequate sealing techniques are available. The needed amounts of potable water are available to supply projected repository requirements without affecting regional availability. Therefore, the evidence does not support a finding that the site is not likely to meet the qualifying condition for preclosure hydrology (level 3).

6.3.3.3.7 Plans for site characterization

Flood studies will be conducted to provide information on flash-flood potential at the site and to assist in determining potential locations for repository surface facilities. Tests to verify the behavior of shaft and borehole seals will also be conducted. Additional information about subsurface hydrologic conditions will be obtained during exploratory shaft construction and in situ testing within the potential host rock. Further analyses will be made of the possible impacts of water withdrawal for repository activities on local and regional ground-water systems.

6.3.3.4 Tectonics (10 CFR 960.5-2-11)

6.3.3.4.1 Introduction

The qualifying condition for this guideline is as follows:

The site shall be located in a geologic setting in which any projected effects of expected tectonic phenomena or igneous activity on repository construction, operation, or closure will be such that the requirements specified in Section 960.5-1(a)(3) can be met.

The objective of this guideline is to ensure that a repository site is in a geologic setting in which any projected effects of expected tectonic phenomena or igneous activity will be such that no unreasonable or unfeasible design features are required. The concerns to be addressed under this guideline are ground motion or ground disruption that might cause damage to repository or transportation facilities, injury to personnel, or the interruption of repository operations, including retrievability.

The guideline consists of one favorable condition, three potentially adverse conditions, one disqualifying condition, and one qualifying condition. The evaluations reported below are summarized in Table 6-42.

6.3.3.4.2 Data relevant to the evaluation

Summary of available data

Most of the data relevant to preclosure tectonics are cited in Section 6.3.1.7 (Postclosure tectonics). Information of special interest for the preclosure period includes an overview (Reiter and Jackson, 1983) of a study by the Nuclear Regulatory Commission (NRC, 1985) about probabilistic evaluations of seismic hazards. Reviews of the impacts of earthquakes on underground facilities have been prepared by Pratt et al. (1978, 1979), Carpenter and Chung (1985), Jackson (1985b), and Owen et al. (1980), and a final report from a workshop on ground motion and tectonics issues at the Yucca Mountain site is available (SAIC, 1986).

A number of sources were used to provide a basis for estimating the feasibility of constructing and operating a repository under possible earthquake ground motion and displacement. Doser (1985) estimated the minimum magnitudes at which surface fault rupture is likely in the Great Basin. Jackson (1985a) reviewed the seismic design bases for other nuclear facilities. Meehan (1984), Merritt et al. (1985) and Reed et al., (1979) discuss designs that have been developed to accommodate fault displacements beneath structures. Brown et al. (1981), Owen and Scholl (1981), and DOI (1972) discuss designs that have been employed where tunnels and pipelines cross active faults. The performance of facilities that were designed to accommodate and have experienced strong ground motion or fault movement is reviewed by Zeevaert and Newmark (1956), Rosenblueth (1960), ENR (1985a,b), Murphy (1973), Meehan, et al. (1973), Stratta et al. (1977), and Yanev (1978). Attenuation relationships for ground motion have been computed by Joyner and Boore (1981) and Campbell (1981).

Table 6-42. Summary of analyses for Section 6.3.3.4; preclosure tectonics (10 CFR 960.5-2-11)

Condition	Department of Energy (DOE) finding
FAVORABLE CONDITION	
The nature and rates of faulting, if any, within the geologic setting are such that the magnitude and intensity of the associated seismicity are significantly less than those generally allowable for the construction and operation of nuclear facilities.	The evidence indicates that this favorable condition is not present at Yucca Mountain: the predicted magnitude and intensity of seismicity are expected to be acceptable but not expected to be significantly less than those generally allowable for the construction and operation of nuclear reactors.
POTENTIALLY ADVERSE CONDITIONS	
(1) Evidence of active faulting within the geologic setting.	The evidence indicates that this potentially adverse condition is present at Yucca Mountain: evidence of active faulting and ground-surface displacement is found within the geologic setting.
(2) Historical earthquakes or past man-induced seismicity that, if either were to recur, could produce ground motion at the site in excess of reasonable design limits.	The evidence indicates that this potentially adverse condition is not present at Yucca Mountain: historical earthquakes or past man-induced seismicity are not expected to cause ground motion at the site that would exceed reasonable design limits.
(3) Evidence, based on correlations of earthquakes with tectonic processes and features (e.g., faults) within the geologic setting, that the magnitude of earthquakes at the site during repository construction, operation, and closure may be larger than predicted from historical seismicity.	The evidence indicates that this potentially adverse condition is not present at Yucca Mountain: no evidence exists to suggest that earthquakes larger than those predicted from historical seismicity could occur during repository construction, operation, and closure.

Table 6-42. Summary of analyses for Section 6.3.3.4; preclosure tectonics (10 CFR 960.5-2-11) (continued)

Condition	Department of Energy (DOE) finding
QUALIFYING CONDITION	
The site shall be located in a geologic setting in which any projected effects of expected tectonic or igneous activity on repository construction, operation, or closure will be such that the requirements specified in Section 960.5-1(a)(3) can be met.	Existing information does not support the finding that the site is not likely to meet the qualifying condition (level 3): tectonics-induced ground motion at the site is expected to be within reasonable design limits for a nuclear facility; there is about a 1 chance in 10,000 for igneous activity over a 10,000-year period. The projected effects of either tectonic or igneous activity in a 90-year period of repository construction, operation, and closure are not likely to be significant.

Assumptions and data uncertainties

The principal assumption made in predicting the tectonism of the region during the preclosure period (assumed to be 90 years) is that the present nature and rate of tectonic processes, as represented by the historical record, will continue into the near future. The major uncertainties in data are attributable to two factors: the historical record of earthquakes in Nevada is relatively brief, and the regional instrumented seismic network at Yucca Mountain has been operating only since 1978. Other key uncertainties are related to estimating the surface accelerations, velocities, and displacements likely to result from an earthquake of a given magnitude at a specified distance from a surface facility. The relationship between earthquake magnitude and fault length may be different for different types of faults (e.g., normal, oblique, and strike-slip) (Bonilla et al., 1984), making this link tenuous for purposes of earthquake prediction and hazard assessment. Uncertainties are also associated with (1) precise definition of seismogenic zones; (2) statistics of the seismic sources within the zones; and (3) appropriateness of attenuation relationships.

6.3.3.4.3 Favorable condition

The nature and rates of faulting, if any, within the geologic setting are such that the magnitude and intensity of the associated seismicity are significantly less than those generally allowable for the construction and operation of nuclear facilities.

Evaluation

Investigations to date covering a 1,100 square-kilometer (425 square-mile) area around the site have found 32 faults that offset or fracture Quaternary deposits. Quaternary faults have been divided into 3 broad age groups: 5 faults last moved between about 270,000 and 40,000 years ago; 4 faults last moved about 1 million years ago; and 23 faults last moved probably between 2 million years and more than 1.2 million years ago (Swadley et al., 1984). Recurrence intervals that have been published for major earthquakes in the region are reviewed in Section 6.3.1.7.5 and summarized in Section 6.3.3.4.5. The historical earthquake record prior to 1978 shows that, within about 10 kilometers (6 miles) of Yucca Mountain, there were 7 earthquakes; 2 had Richter magnitudes of M = 3.6 and M = 3.4; magnitudes were not reported for the remaining 5 earthquakes. They were apparently very small or had magnitudes that could not be determined due to instrument problems. Prior to 1978, however, standard errors of most locations were ± 7 kilometers (± 4.2 miles) or more. A local seismic network with significantly increased detection and location capability has recorded 3 microearthquakes in the same area between August 1978 and the end of 1983. The largest magnitude was approximately M = 2.0 on the Richter scale (Rogers, 1986).

The peak historic acceleration at a location 20 kilometers (12 miles) east of Yucca Mountain was estimated to be less than 0.1g (Rogers et al., 1977). Using similar methods, the seismic hazard for Yucca Mountain was estimated under the assumption that Yucca Mountain faults are not active.

The U.S. Geological Survey deterministically estimated that the most likely peak acceleration at Yucca Mountain would be approximately 0.4g (USGS, 1984). This acceleration was estimated to result from a full length fault rupture (length, 17 kilometers (11 miles), magnitude 6.8) on the Bare Mountain Fault, which is 14 kilometers (9 miles) west of the Yucca Mountain site. Alternative probabilistic hypotheses (USGS, 1984), formulated on the basis of historical rates of seismicity in surrounding regions, and assumptions that earthquakes can occur anywhere in the region including Yucca Mountain, have resulted in estimates that 0.4g has a return period on the order of 900 to 30,000 years. The range of return periods are derived from the use of two different models for the relationship between maximum acceleration and return period. The probability that 0.4g will be exceeded in 90 years, the assumed duration of the preclosure period, under these hypotheses is estimated to be between 0.003 and 0.1 (USGS, 1984). The probabilistic results discussed by Rogers et al. (1977) and USGS (1984) demonstrate that large uncertainties exist in the evaluation of seismic hazard. Different assumptions regarding the appropriate recurrence model, attenuation relationships, and the identification of specific faults as seismic sources can result in widely different estimates of surface acceleration for a given probability. At this time, it is premature to place much confidence in these estimates, other than using them to provide insight until a more complete assessment can be made of the various input parameters that are required for a probabilistic seismic hazard analysis. The estimates by USGS (1984) are in reasonable agreement with previously published estimates of recurrence intervals for major earthquakes in the region surrounding the Nevada Test Site (NTS) which are on the order of 25,000 years for $M \geq 7$ and 2,500 years for $M \geq 6$. Recurrence intervals estimated for $M \geq 7$ earthquakes for the region south and east of Yucca Mountain are longer than those for the NTS region by about a factor of 7. Until detailed fault studies are completed, it will not be possible to determine which of the recurrence intervals are most appropriate for the faults near Yucca Mountain (see Section 6.3.1.7.5).

There are no present intentions to use the same seismic design procedures for waste repositories as have been required for nuclear power plants. The Nuclear Regulatory Commission (NRC) has indicated that no seismic requirements have yet been established for nuclear repositories (NRC, 1985). They note that all repository structures, systems, and components important to safety will be reviewed to establish appropriate design requirements, and that all requirements will be developed to ensure compliance with 10 CFR Part 60 (1983) and 40 CFR Part 191 (1985). However, in order to establish a consistent interpretation of this favorable condition, seismic design values for commercial nuclear power plants that have been licensed by the NRC were examined (Jackson, 1985a). Because most nuclear plants have been built in the east where peak acceleration estimates are low, this compilation shows that about 90 percent of reactors have a safe shutdown earthquake acceleration value that is equal to or less than 0.20g. It should be noted that design limits of 0.75g and 0.67g for plants licensed in areas of high seismic activity have been accepted (Jackson, 1985a).

A description of the approach to be used in establishing the appropriate seismic design requirements for a repository at Yucca Mountain is outlined in Section 6.3.3.4.5. Using this approach, the seismogenic potential of faults in the area will be established, and the appropriate seismic design values will be determined. Because the only acceleration estimate presently available is for a fault that is not at or near the site, a conservative position on this favorable condition is appropriate for the Yucca Mountain site.

Conclusion

Preliminary deterministic estimates of the ground motion that could result from the largest earthquake associated with a potentially active fault, 14 kilometers (9 miles) west of the Yucca Mountain site, predict a peak ground acceleration of about 0.4g. Acceleration estimates for ground motion resulting from earthquakes on potentially active faults that are closer to the Yucca Mountain site are not available. With the assumption that 0.20g is the peak acceleration that is generally allowable for nuclear facilities, the probable peak acceleration that will be determined for the Yucca Mountain site is not likely to be significantly smaller than 0.20g. Therefore, the evidence indicates that this favorable condition is not present at Yucca Mountain.

6.3.3.4.4 Potentially adverse conditions

(1) Evidence of active faulting within the geologic setting.

Evaluation

There is geologic evidence of Quaternary faulting in the regional geologic setting of Yucca Mountain. Fault scarps, nearly all small and considerably eroded, are present within the region (Carr, 1984). The area has been mapped and studied in sufficient detail to render it unlikely that important fault scarps are undetected. No confirmed surface displacement younger than 40,000 years had been demonstrated at or near Yucca Mountain at the time of publication of Swadley et al. (1984). New data, available in the form of preliminary thermoluminescence dates, may indicate on the order of 1 to 10 centimeters of fault displacement in the eastern Crater Flat area more recently than about 6,000 years ago (Dudley, 1985) (see also Section 6.3.1.7.4, potentially adverse condition 1). Thermoluminescence is a dating technique that has been used in archaeology, but has not yet been shown to provide reliable dates in geologic applications.

Thirty-two faults within a 1,100 square-kilometer (425 square-mile) area around the site offset or fracture Quaternary deposits. Five faults are thought to have last moved between about 270,000 and 40,000 years ago; 4 faults last moved about 1 million years ago; and 23 faults are thought to have last moved between 1 and 2 million years ago (Swadley et al., 1984). Published data on estimates of recurrence intervals for major earthquakes in the Basin and Range Province are compiled in Section 6.3.1.7.5. For the Nevada Test Site (NTS) region, the recurrence interval for $M \geq 7$ earthquakes appears to be on the order of 25,000 years, and the average for the area north of the NTS appears to be on the order of 7,000 to 10,000 years. For $M \geq 6$, the recurrence interval is reported to be on the order of 2,500 years for the NTS region. It should be noted that wide variability results from using different assumptions and regions in the estimation of recurrence intervals.

Within about 10 kilometers (6 miles) of Yucca Mountain, historical seismic records before 1978 show that 7 earthquakes were recorded; of these, 2 had magnitudes of M = 3.6 and M = 3.4; magnitudes were not reported for the remaining 5 earthquakes. They were apparently very small, or had magnitudes that could not be determined due to instrument problems. A local seismic network with significantly increased detection and location capability has recorded 3 microearthquakes in the same area between August 1978 and the end of 1983. The largest magnitude (M_L), was approximately M = 2 on the Richter scale (Rogers, 1986).

Conclusion

During the Quaternary Period, faulting occurred within 10 kilometers (6 miles) of Yucca Mountain. Historical seismic records and recent seismicity at and near the site indicate that faulting is an ongoing process within the geologic setting. Therefore, the evidence indicates that this potentially adverse condition is present at Yucca Mountain.

(2) Historical earthquakes or past man-induced seismicity that, if either were to recur, could produce ground motion at the site in excess of reasonable design limits.

Evaluation

Calculations for the maximum acceleration expected at Yucca Mountain from ground motion induced by underground nuclear explosions at the NTS give a mean acceleration of 0.061g and a mean plus 3 standard deviations of 0.32g (Section 6.2.1.5). As discussed in the evaluation of the favorable condition under this guideline, the peak historical acceleration from a natural earthquake at a location 20 kilometers (12 miles) east of Yucca Mountain was estimated to be less than 0.1g (Rogers et al., 1977).

Two earthquakes with a magnitude of M = 6 have occurred within about 200 kilometers (125 miles) of Yucca Mountain: one occurred in 1908, 110 kilometers (68 miles) southwest of Yucca Mountain, and one occurred in 1966, about 210 kilometers (130 miles) to the northeast (USGS, 1984). If these earthquakes recurred, they would not be large enough or close enough to Yucca Mountain to produce ground motion requiring designs in excess of reasonably available technology.

There are presently no plans to apply the same seismic design procedures to waste repositories that have been required for nuclear power plants. The Nuclear Regulatory Commission (NRC) has indicated that no seismic requirements have yet been established for nuclear waste repositories (NRC, 1985). They note that all repository structures, systems, and components important to safety will be reviewed to establish appropriate design requirements, and that all requirements will be developed to ensure compliance with 10 CFR Part 60 (1983) and 40 CFR Part 191 (1985). However, in order to evaluate this favorable condition, the maximum seismic acceleration values for reactors that have been licensed by the NRC for safe shutdown earthquakes (SSE) were reviewed (Jackson, 1985a). The maximum levels occur in California in high seismic activity zones where the Diablo Canyon reactor has been licensed for an SSE of 0.75g, and the San Onofre units for 0.67g.

It is important to note that the safe shutdown requirements for a reactor are not relevant for a repository. The inventory of primary-system cooling water in a reactor must be maintained after a seismic event in order to control core decay heat, prevent meltdown, and prevent potential release of short-lived noble gases or particulates. In a repository, the short-lived isotopes no longer exist, and the heat that will be generated is several orders of magnitude less than that for a reactor. This heat can be contained within the facility without dependence on complex mechanical or hydraulic systems operating after a seismic event. Section 6.3.3.4.5 reviews technology that has been used in other facilities to incorporate designs for both displacement and ground motion from earthquakes. Given the current state of knowledge of the estimates for recurrence rates for large earthquakes in the region which includes the Yucca Mountain site, and the record of historical seismicity within the East-West Seismic Belt, there is no evidence that suggests that ground motion at the site during the preclosure time period is likely to be in excess of reasonable design limits.

Conclusion

If historical earthquakes or past man-induced seismicity were to recur at Yucca Mountain, the resulting ground motion would be within reasonable design limits. Therefore, the evidence indicates that this potentially adverse condition is not present at Yucca Mountain.

(3) Evidence, based on correlations of earthquakes with tectonic processes and features (e.g., faults) within the geologic setting, that the magnitude of earthquakes at the site during repository construction, operation, and closure may be larger than predicted from historical seismicity.

Evaluation

Two historical earthquakes of magnitude M = 6 have occurred within about 200 kilometers (125 miles) of the Yucca Mountain site: one in 1908 at Death Valley 110 kilometers (68 miles) southwest of Yucca Mountain, and one in 1966 about 210 kilometers (130 miles) northeast of the site. Within about 10 kilometers (6 miles) of Yucca Mountain, historical seismic records before 1978 show that 7 earthquakes were recorded: of these, 2 had magnitudes of M = 3.6 and M = 3.4; magnitudes for the remaining 5 were not reported. They were apparently very small or had magnitudes that could not be determined due to instrument problems. A local seismic network with significantly increased detection and location capability has recorded 3 microearthquakes in the same area between August 1978 and the end of 1983. The largest magnitude (M_L) was approximately M = 2 on the Richter scale (Rogers, 1986).

For the purposes of evaluation of this condition, it will be assumed that historic seismicity is representative of the earthquake potential for the Yucca Mountain site for short periods of time, such as the preclosure time frame. This evaluation will, therefore, not consider design events or ground motions that are associated with low-probability scenarios, because the likelihood of a larger-than-historic event is low during the preclosure period.

Given the present status of earthquake-hazard assessment, there is no evidence that earthquakes larger than those observed in the historical records for the geologic setting are likely to occur at Yucca Mountain during the 90-year preclosure period. Published estimates of recurrence intervals for earthquakes are reviewed in Section 6.3.1.7.5, for the region that includes the Yucca Mountain site. Recurrence intervals for $M \geq 7$ earthquakes are reported to be on the order of 25,000 years; for $M \geq 6$, recurrence intervals are on the order of 2,500 years; and, for $M \geq 5$, estimates of recurrence intervals are about 250 years.

Conclusion

Seismicity at the site since 1978 has been manifested by earthquakes with magnitudes less than 2, although larger earthquakes have occurred within the geologic setting. There is no evidence that earthquakes larger than those predicted from historical seismicity within the geologic setting should be expected to occur at the site during the assumed 90-year period of repository construction, operation, and closure. Therefore, the evidence indicates that this potentially adverse condition is not present at Yucca Mountain.

6.3.3.4.5 Disqualifying condition

A site shall be disqualified if, based on the expected nature and rates of fault movement or other ground motion, it is likely that engineering measures that are beyond reasonably available technology will be required for exploratory shaft construction or for repository construction, operation, or closure.

Evaluation

Within about 10 kilometers (6 miles) of Yucca Mountain, historical earthquake records before 1978 show that 7 earthquakes were recorded; 2 had magnitudes of M = 3.6 and M = 3.4; magnitudes were not reported for the remaining 5. They were apparently very small or had magnitudes that could not be determined due to instrument problems. Prior to 1978, however, standard errors of most earthquake locations were $\pm$ 7 kilometers ($\pm$ 4.2 miles) or more. A local seismic network has recorded 3 microearthquakes in the same area between August 1978 and the end of 1983. The largest magnitude (M_L, Richter scale) was approximately M = 2 (Rogers, 1986). Two historical earthquakes of magnitude M = 6 occurred within about 200 kilometers (125 miles) of the Yucca Mountain site, one in 1908 at Death Valley, 110 kilometers (68 miles) southwest of Yucca Mountain and one in 1966, about 210 kilometers (130 miles) northeast of the site.

Thirty-two faults within a 1,100-square-kilometer (425-square-mile) area around the site offset or fracture Quaternary deposits. Five faults are thought to have last moved between about 270,000 and 40,000 years ago; 4 faults last moved about 1 million years ago; and 23 faults are thought to have last moved between 1 and 2 million years ago (Swadley, et al., 1984). At the time of publication of Swadley et al. (1984), no evidence of offset younger than 40,000 years had been confirmed; recently available, but unevaluated, thermoluminescence dates may indicate on the order of 1 to 10 centimeters of fault displacement in eastern Crater Flat more recently than about 6,000 years ago (Dudley, 1985).

Previously published estimates of recurrence intervals for earthquakes were reviewed in Section 6.3.1.7.5. The region including the Yucca Mountain site is reported to have an estimated recurrence interval for $M \geq 7$ on the order of 25,000 years; for $M \geq 6$, the recurrence interval is on the order 2,500 years; and for $M \geq 5$, the recurrence interval is reported to be on the order of 250 years. The range of rerupture times for major earthquakes presented in Table 6-36 in Section 6.3.1.7.5 reflects the location of the site on the boundary between two zones with very different levels of seismic activity. One zone is to the south of the site with a very low level of seismicity and very long recurrence intervals for large earthquakes (on the order of 190,000 years for $M \geq 7$ for the region including Las Vegas); the other zone is the region to the north where recurrence intervals are on the order of 7,000 to 10,000 years for $M \geq 7$. The range in estimates of recurrence intervals demonstrates the wide variability that results for differing regions when a wide variety of assumptions are used. At this time, these values can only provide insight regarding possible recurrence intervals for faults near Yucca Mountain. Until detailed fault studies are fully completed, there is large uncertainty regarding the appropriate recurrence intervals for these faults. However, the available data (Swadley et al., 1984; Dudley, 1985; and USGS, 1984) show no evidence to suggest that recurrence intervals would be shorter than on the order of 25,000 years for major ($M \geq 7$) earthquakes. It should also be noted that there is no information currently available on the seismogenic potential of faults at or near Yucca Mountain, so that the occurrence of a magnitude 7 earthquake in the area can neither be anticipated nor can it be ruled out. Although USGS (1984) indicates that fault movement with surface displacements are possible at or near the site, recurrence interval data suggest that earthquakes that are large enough to generate major surface displacements are unlikely for the preclosure time period of less than 100 years. Doser (1985) reports that minimum earthquake magnitudes of 6.0 to 6.5 are required to produce surface breakage in the Intermountain Seismic Belt.

The only available estimate of acceleration at the Yucca Mountain site was made under the assumption that faults at the site were not active. The most likely peak acceleration at Yucca Mountain was deterministically estimated to be approximately 0.4g (USGS, 1984). This acceleration was estimated to result from a full length fault rupture (length, 17 kilometers (11 miles), magnitude 6.8) on the Bare Mountain Fault, which is 14 kilometers (9 miles) west of the Yucca Mountain site. Alternative probabilistic hypotheses, formulated on the basis of historical rates of seismicity in surrounding regions, and assumptions that earthquakes can occur anywhere in the region including Yucca Mountain, can be used to show that 0.4g has a return period on the order of 900 to 30,000 years. The probability of 0.4g being exceeded in 90 years, the assumed duration of the preclosure period, under these hypotheses is estimated to be between 0.003 and 0.1 (USGS, 1984). These values are in reasonable agreement with previous estimates of recurrence intervals for the region. The probabilistic results discussed by Rogers et al. (1977) and USGS (1984) demonstrate that large uncertainties exist in the evaluation of seismic hazard. Different assumptions regarding the appropriate recurrence model, attenuation relationships, and the identification of specific faults as seismic sources, can result in widely different estimates of acceleration for a given probability. At this time, it is premature to place much confidence in these estimates, other than using them to provide insight until a more complete assessment can be made of the various input parameters that are required for a probabilistic seismic hazard analysis.

Possible effects on the preclosure operation of a repository from earthquakes at or near the site can be considered from the standpoint of the potential for ground motion and the possibility of surface displacement. As discussed in potentially adverse condition 2, nuclear reactors have been designed and licensed by the Nuclear Regulatory Commission with safe shutdown earthquake accelerations of 0.75g and 0.67g in seismically active areas.

Owen et al. (1980) review the seismic design considerations that may be applicable to the underground portion of a repository. Experience with strong ground motion acting on other types of structures also provides useful information. For the underground portion of the repository, evidence is available from a number of mines and tunnels in which earthquake damage at depth is reported to be less than at the surface (Pratt et al., 1978). In a review of the effects of earthquakes on underground facilities, (Carpenter and Chung, 1985), the following tentative conclusions are presented. If fault displacement occurs through a site, damage is inevitable; however, damage from shaking alone is generally confined to facilities located within the epicentral region and may be less than damage to surface facilities at the same site. There is an apparent reduction of amplitude with depth, although seismic data for this observation is reported to be mixed. The frequency content of motion is important to the stability of underground openings, and attenuation relationships should be site specific. Model studies indicate that problems may occur in shafts, particularly with waste-handling equipment. This illustrates the need for detailed assessments of the seismic aspects of shaft designs, hoists, and in-shaft waste-handling equipment. All of the above information will be considered during seismic hazard studies of the Yucca Mountain site. Jackson (1985b) reviewed the literature on damage to underground facilities from earthquakes. He notes that there are numerous observations that underground structures suffer less damage than surface structures during strong shaking motion. Jackson (1985b) qualitatively concludes that the probability of events that are large enough to cause damage is likely to be low (10^{-4} to 10^{-5} per year) for the preclosure repository time frame. He also points out that damage to subsurface facilities is likely to be localized so that few waste disposal containers would be affected, although systems used for retrieval, such as the shaft, hoist, and transportation systems may require careful consideration regarding seismic design requirements in support of the Carpenter and Chung (1985) conclusions reviewed above. In general, damage is not likely to occur unless the underground facility is very close to an earthquake epicenter. The primary cause of earthquake-induced failure in underground excavation is apparently movement along preexisting faults or collapse at the portal of a tunnel or shaft.

Seismic designs to accommodate fault displacements have been developed for other facilities including large buildings. The effects of fault displacement on the performance of structures may depend on whether the faults are parallel or perpendicular to building walls and on the thickness and characteristics of soil above bedrock (Meehan, 1984). Merritt et al. (1985)

point out that although the absolute amplitude of displacement may be large, this displacement is often spread over a long length, and that the amount of distortion at any point is generally small, often within the elastic deformation capacity of the structure. State-of-the-art technology allows designs that incorporate flexible joints so that the effects of minor fault movement can be accommodated. Critical areas of a structure could also be isolated by a sand cushion or other displacement accommodating materials (Meehan, 1984).

The questions raised in design and licensing for a waste-handling building (WHB) that spans a surface displacement are significant. A preferable design solution for the geologic setting of Yucca Mountain will be to locate the WHB, which will contain the surface inventory of spent fuel and high-level waste, on a location where surface displacements have not occurred. This building location need be only 152 meters (500 feet) square. Because of the juxtaposition of surface and subsurface facilities at the Yucca Mountain site, there is an extensive area that could be acceptable for the WHB location. Early design studies are intended to establish one or more suitable locations for the WHB where surface fractures are not present. Establishing a suitable WHB location using this philosophy will be preferable to the design and licensing of the facility using seismic design technology described above.

A review of the information available on designs to accommodate fault displacement in non-nuclear facilities shows that many structures have been designed to accommodate offset. For tunnels that cross active faults, an approach used in the California aqueduct where it crosses the Garlock Fault was to design a reinforced concrete conduit; another approach was described for the Bay Area Rapid Transit (BART) System, where tunnels cross the Hayward Fault in Berkeley, California. The Hayward Fault has an estimated annual creep rate of between 6 and 8 millimeters (0.24 and 0.31 inch) per year (Brown et al., 1981). The BART tunnel was oversized and lined with closely spaced steel rib sections to permit absorption of tectonic deformations and promote rapid repair and track realignment (Owen and Scholl, 1981). From experience of damage to underground box conduits during the San Fernando earthquake, suggestions for design of reinforced concrete conduits include the following: close-spaced seismic joints; construction joints and seismic joints placed in the same vertical plane; and avoidance of changes in geometry or properties of the cross section, sudden change of direction, and confluence near an active fault zone. Merritt et al. (1985) suggest a structural design goal that may be appropriate in some cases which is to provide sufficient ductility to absorb the imposed deformation without losing the capacity to carry static loads. The Trans-Alaskan Pipeline was designed to traverse active fault zones having 0.6 meters (2 feet) of horizontal and/or vertical displacement (DOI, 1972). Table 6-43 summarizes information on a number of facilities that have experienced strong ground motion or fault movement.

In the well-known case of the General Electric Test Reactor, located in Pleasanton, California, a comprehensive structural analysis was completed of the safety-related components and systems for both surface displacement and maximum vibratory ground motion. Using an assumption of 1 meter (3 feet) of offset, an analysis of the reactor building suggested that induced stresses in the concrete core structure would be much less than the cracking threshold capacities (Reed et al., 1979).

Table 6-43. Facilities that were designed for and have experienced strong ground motion or fault movement

Facility	Source of Ground Motion	Observed Effects	Reference
Fukushima Nuclear Power Plant, units 1 through 5. Fukushima Prefecture, Japan. Location approximately 125 km from epicenter; 0.12g lateral ground acceleration; 0.25g maximum peak response acceleration of the structures.	Miyagi-Ken-oki, Earthquake June 12, 1978 Magnitude 7.4 Focal depth ~ 30 km Offshore location	Damage was negligible. Reactors apparently did not shut down and all 5 units were operating 11 days later.	Yanev (1978)
Latino Americano Tower, Mexico City, Mexico. 43 to 44 stories high. Location approximately 350 km from epicenter; 0.05 to 0.1g lateral acceleration (1957); 0.18g acceleration (1985).	Mexico earthquakes July 28, 1957 Magnitude 7.5 Focal depth 25 km September 19, 1985 Magnitude 8.1 September 20, 1985 Magnitude 7.5	Building survived the earthquake without damage.	Zeevaert and Newmark (1956); Rosenblueth (1960) ENR 1985a ENR 1985b
Bunker Hill Tower, Los Angeles, California. 32 stories high; location approximately 25 km from epicenter.	San Fernando Earthquake February 9, 1971 Magnitude 6.4		Murphy 1973
Banco de America, Managua, Nicaragua. 17 stories high. Located immediately adjacent to fault that moved during earthquake; concrete shear wall construction.	Managua, Nicaragua, Earthquake December 23, 1972 Magnitude 6.25	Overall earthquake damage very light. The shear walls exhibited only very minor cracking. Most floors and wall areas exhibited no signs of damage.	Meehan et al. (1973)

Table 6-43. Facilities that were designed for and have experienced strong ground motion or fault movement (continued)

Facility	Source of Ground Motion	Observed Effects	Reference
Tiaon Building, Cotabato City, Mindanao, Philippines. 4 stories high. Location approximately 100 km from epicenter; moment frame concrete; 0.08 to 0.18g peak acceleration.	Mindanao, Philippines, Earthquake August 17, 1976 Magnitude 7.8 Focal depth less than 33 km.	Survived the earthquake without structural damage and only a slight crack in a concrete block partition.	Stratta et al. (1977)
Bay Area Rapid Transit Tunnel (BART), Oakland, California. Tunnel penetrates Hayward Fault. Designed to accommodate both continuous fault creep and periodic fault displacement associated with earthquakes.	Hayward Fault Creep--6 to 8 mm per year laterally. Historical fault movement (up to 1.5 m) associated with earthquakes in late 1800s.		Brown et al. (1981)

Methodology for assessing significance of seismic and tectonic events

A detailed description of the approach utilized to identify and resolve licensing issues associated with significant seismic and tectonic events is being prepared by the Nevada Nuclear Waste Storage Investigations (NNWSI) Project and will be incorporated in the site characterization plan. Significant seismic and tectonic events are those events that, in light of tectonic history and other characteristics of the site, must be considered in evaluating compliance of the repository with the performance objectives of 10 CFR Part 60 (1983). This description, to be presented as a position paper for discussion with the NRC and the public, will address the formulation of criteria to be used for identifying the significant seismic and tectonic events to be considered for preclosure and postclosure analyses. On a preliminary basis, the position paper will identify scenarios to be addressed in these analyses, including those related to faults at or near the site. A rationale will be developed to explain why certain scenarios should be excluded or included in the analyses on the basis of either probability or consequence. The paper will also evaluate the potential impact of the relevant scenarios on the NRC performance objectives and on underground and surface facility design.

An issue-resolution strategy will also be developed. The specific seismic and tectonic events considered for analysis will be discussed in terms of uncertainties in scenario definition and data and assumptions to be used in analyses. The approach to be used to demonstrate compliance could incorporate several sequential steps. First, the set of release scenarios for the seismic and tectonic events that could affect safety during operation and retrieval would be identified. Next, failure-mode analyses of structures, systems, and components important to safety would be conducted using seismic-initiating-event probabilities and seismic-design parameters determined in accordance with procedures described in the paper. These analyses would be used to determine likely and maximum consequences of failure with respect to radiological safety, considering the ranges of parameters that affect these consequences. The results of these determinations would then be used in an analysis and assessment of the degree of compliance with applicable release limits. Finally, the uncertainty in these analyses and assessments would be evaluated. The resulting information would be used in an evaluation of the impact on design of structures, systems, and components important to safety and to determine the implications regarding the design of structures to resist failure. The above steps will be iterated and will become more sophisticated as data from site characterization becomes available. An iterative approach will also be used to define and refine field programs to obtain the necessary data.

The process just described recognizes that many of the analyses and supporting investigations involve state-of-the-art concepts regarding the acquisition and use of geologic data in sophisticated analyses. While such concepts will be applied for the first time to a repository, the NRC has evaluated numerous probabilistic risk assessments for nuclear reactors, which include seismic initiating events. Techniques discussed above are likely to be similar to those that have been used for probabilistic risk assessments. The analyses, design criteria, and evaluation criteria prepared by the NNWSI Project will be presented in an open forum to ensure that the best technical approaches are incorporated in the subsequent evaluation of the tectonics disqualifying condition and qualifying condition of 10 CFR Part 960 (1984), the performance objectives of 10 CFR Part 60 (1983), and evaluations of worker and public health and safety.

Conclusion

There may be evidence for a very small amount of surface displacement near Yucca Mountain in the past 6,000 years. The closest historical M = 6 earthquake occured in 1908 about 110 kilometers (68 miles) southwest of the site. Recurrence intervals for earthquakes in the region are reported to be on the order of 25,000 years for M $\geq$ 7 earthquakes, and on the order of 2,500 years for M $\geq$ 6 earthquakes. On the basis of present knowledge of past earthquakes and fault locations, a review of currently available design technology, and the plans for identifying the significant seismic and tectonics parameters during site characterization, it is judged feasible to construct, operate, and decommission an exploratory shaft facility and a radioactive waste repository at Yucca Mountain. Therefore, the evidence does not support a finding that the site is disqualified (level I).

6.3.3.4.6 Evaluation and conclusion for the qualifying condition on the preclosure tectonics guideline

Evaluation

The brief historical seismic record at Yucca Mountain shows no earthquakes that have produced damaging ground motion (Rogers et al., 1983; Rogers et al., 1977; USGS, 1984). Within 20 kilometers (12 miles) of Yucca Mountain, the deterministically predicted maximum credible earthquake (M = 6.8) on any of the largest of the nearby faults considered seismically active could produce a 0.4g acceleration at Yucca Mountain (USGS, 1984). This earthquake has a predicted return period on the order of 900 to 30,000 years. Published recurrence intervals for earthquakes in the region are reported to be on the order of 25,000 years for M $\geq$ 7 earthquakes; on the order of 2,500 years for M $\geq$ 6 earthquakes; and, about 250 years for M $\geq$ 5 earthquakes. The estimated rupture length of a fault producing an earthquake of a given magnitude and the maximum distance from that fault to a given mean and peak horizontal acceleration are given in Table 6-44. The magnitude-length relationship was derived from western North American earthquakes by Bonilla et al. (1984). The 84th-percentile and mean accelerations of Joyner and Boore (1981) and Campbell (1981) were used to compute conservative estimates of the distances listed in the table. At this time, it has not been determined what percentile will be appropriate for ground motion estimates for a repository. Section 6.3.3.4.5 discusses the methodology that will be used to assess the significance of possible seismic and tectonic events and to establish the required level of conservatism. Additionally, the values presented in Table 6-44 are provided to show a range of peak acceleration values for different sized earthquakes at a variety of distances. Until final evaluations of the faults near the site, appropriate assumptions for fault length, displacement, and earthquake magnitude are not possible or warranted. Table 6-44 shows that to produce peak accelerations in excess of those that have been accepted for reactors would require a large event very close to the site. Given the

Table 6-44. Magnitude vs. fault length and distance from fault to peak horizontal accelerations

Magnitude, M	Fault length, L[a] (kilometers)	Calculation method	Distance to acceleration[b,c] kilometers 0.2g	0.5g	0.75g	1.0g
5.5	5	(d)	8/17	-/3	-/4	-/-
		(e)	5/8	1/2	-/1	-/-
6.0	9	(d)	12/22	-/7	-/-	-/-
		(e)	8/13	1/3	-/1	-/-
6.5	17	(d)	16/29	2/11	-/-	-/-
		(e)	12/19	2/5	-/2	-/-
7.0	33	(d)	22/38	6/16	-/10	-/5
		(e)	18/28	3/8	-/3	-/-

[a] Computed from Bonilla et al. (1984) western North American data. Log L = 0.566M-2.44 where M = surface wave magnitude.

[b] The numbers before and after the slash are the 50th and 84th percentile accelerations, respectively.

[c] Hyphen (-) indicates that these events are not likely to generate the given accelerations.

[d] Computed from Joyner and Boore (1981) 50th and 84th percentile acceleration relationships.

[e] Computed from Campbell (1981) 50th and 84th percentile acceleration relationships.

regional estimates of recurrence rates for $M \geq 7$ on the order of 25,000 years and about 2,500 years for $M \geq 6$, the probability of occurrence of a damaging earthquake during the 90-year preclosure period is likely to be very small. Furthermore, the fault lengths observed in the immediate vicinity of Yucca Mountain do not appear sufficient to generate earthquakes with magnitudes greater than 6 or 6.5 regardless of the recurrence intervals. As noted in the evaluation of the disqualifying condition, reasonably available technology should be sufficient to accommodate the seismic design requirements for the site when they are established during site characterization.

From the standpoint of seismic hazard, Reiter and Jackson (1983) point out that an approach based on return periods on the order of 1,000 or 10,000 years have been implicitly accepted by the Nuclear Regulatory Commission (NRC) for developing the seismic design criteria for nuclear reactors. Such an approach may be overly conservative for a geologic repository. The concept of continuing operation of complex systems after a seismic event must be applied to a reactor at the safe shutdown earthquake level, but is not relevant for a repository surface facility. The primary-coolant water supply for a reactor must continue to be available for core cooling after the seismic event. Because of the presence of short-lived isotopes, the fuel in a reactor core will continue to generate decay heat at a rate several orders of magnitude higher than the repository spent fuel. The noble gases xenon and krypton are of particular concern and must be contained along with iodine-131 to protect public health and safety. This requirement necessitates the continued functioning of complex mechanical and hydraulic systems during and after a maximum seismic event as well as the maintenance of the full structural integrity of the containment building. In a repository, the spent fuel or defense high-level waste decay heat is low enough to require only passive systems. Passive dry storage casks are presently before the NRC for licensing for reactor site storage of spent fuel.

After emplacement in the underground facility, waste disposal containers are unlikely to experience velocities or accelerations that approach the velocities and accelerations that will be simulated in drop tests to determine strength for handling purposes. An acceleration of 1g at repository depth is extremely unlikely; containers will be designed and tested for impact velocities that produce accelerations of more than 10 times this value.

The volcanic hazard potential at the site from silicic volcanism is much less than that for basaltic volcanism as discussed in Section 6.3.1.7.3. The possible effects and probability of basaltic volcanism at Yucca Mountain during the preclosure period are thoroughly reviewed in sections 6.3.1.7.3 and 6.3.1.7.6. The probability of a recurrence of basaltic volcanism causing disruption of the repository facility ranges between 3.3×10^{-6} and 3.0×10^{-8} for the 90-year preclosure period. Because of the low probabilities and small consequences, the risk posed by basaltic volcanism is judged to be very small during the preclosure period (Link et al., 1982).

Conclusion

The only tectonic activity expected to affect Yucca Mountain during the preclosure period is the occurrence in the surrounding region of small-magnitude earthquakes. Such activity is likely to produce ground motion that is presently judged to be within the design limits likely to be applied to nuclear repositories and is compatible with the requirements specified in 10 CFR 960.5-1(a)(3) (1984). Therefore, on the basis of the above evaluation, the evidence does not support a finding that the site is not likely to meet the qualifying condition for preclosure tectonics (level 3).

6.3.3.4.7 Plans for site characterization

During site characterization, field investigations will be continued to further evaluate tectonic activity at the Yucca Mountain site and in the surrounding region (see Section 6.3.1.7, Postclosure tectonics, for a complete discussion). Site-specific attenuation curves will be developed to better predict expected ground motion. Potentially active faults in the area will be carefully evaluated to determine their slip rates and their characteristics.

6.3.4 PRECLOSURE SYSTEM GUIDELINE

The three preclosure system guidelines establish the overall objectives to be met by a repository during repository siting, construction, operation, and closure. They address (1) preclosure radiological safety; (2) the environmental, socioeconomic, and transportation-related effects associated with repository development and operation; and (3) the ease and cost of repository siting, construction, operation, and closure. The first two do not require site characterization for the demonstration of compliance; they are discussed in Section 6.2.2. The third preclosure system guideline does require site characterization; a preliminary evaluation of the Yucca Mountain site against this system guideline is presented in this section.

6.3.4.1 Ease and cost of siting, construction, operation, and closure (10 CFR 960.5-1(a)(3))

6.3.4.1.1 Introduction

The qualifying condition for this guideline is as follows:

Repository siting, construction, operation, and closure shall be demonstrated to be technically feasible on the basis of reasonably available technology, and the associated costs shall be demonstrated to be reasonable relative to other available and comparable siting options.

The preclosure system guideline on the ease and cost of siting, construction, operation, and closure is ranked lowest in importance among the three preclosure system guidelines because it does not relate directly to the health, safety, and welfare of the public or the quality of the environment. The elements pertinent to this guideline are (1) the site characteristics that affect siting, construction, operation, and closure; (2) the engineering, materials, and services necessary to conduct these activities; (3) written agreements between the U.S. Department of Energy and the affected State, and the Federal regulations that establish the requirements for these activities; and (4) the repository personnel at the site during siting, construction, operation, or closure.

This guideline would not be met if a large number of special measures were necessary because the site had unsuitable surface features; because the host-rock characteristics, including thickness, lateral extent, and geomechanical properties, required technology beyond that available at reasonable cost; because the hydrologic conditions at the site could limit the effectiveness of repository seals or cause flooding in the underground workings; or because the potential for tectonic activity required unreasonable or infeasible design features to protect the workers or the public. Table 6-45 summarizes the finding for the qualifying condition.

6.3.4.1.2 Data relevant to the evaluation

The information presented in this section is derived from those for the technical guidelines on surface characteristics (Section 6.3.3.1), rock characteristics (Section 6.3.3.2), hydrology (Section 6.3.3.3), and tectonics (Section 6.3.3.4). This information is preliminary because the data needed from the site-characterization program are not yet available. Furthermore, only preliminary concepts of the repository design have been identified (MacDougall, 1985). Five important variables are considered in the following evaluation: (1) the location of surface features; (2) the method of access to the underground facility; (3) the depth of the emplacement level; (4) the size and shape of the underground facility; and (5) the method of waste emplacement. These variables will be reevaluated and further refined during the conceptual design of the repository. The conceptual design will, in turn, be evaluated with the information obtained during site characterization. After site characterization, and the completion of a preliminary (Title I) design, more precise estimates of the ease and cost of siting, construction, operation, and closure will be possible.

The discussions that follow describe the activities involved with repository construction, operation, and closure and evaluate each of the three phases in terms of the available technology. It is assumed that 10 percent of the access drifts, emplacement drifts, and holes would be excavated and stabilized during construction and that the remainder would be excavated and stabilized during operation.

6.3.4.1.3 Evaluation

<u>Evaluation for repository siting</u>

Siting activities include: (1) the construction of the exploratory shaft facility; (2) the construction of a secondary egress shaft; (3) the construction of surface and support facilities, including trailers to house offices, medical services, and change rooms, as well as utility systems, head

Table 6-45. Summary of analyses for Section 6.3.4.1; preclosure system guideline: ease and cost of siting, construction, operation, and closure (10 CFR 960.5-1(a)(3))

Condition	Department of Energy (DOE) finding
QUALIFYING CONDITION	
Repository siting, construction, operation, and closure shall be demonstrated to be technically feasible on the basis of reasonably available technology, and the associated costs shall be demonstrated to be reasonable relative to other available and comparable siting options.	Existing information does not support the finding that the site is not likely to meet the qualifying condition (level 3): no special technology is expected to be required; repository activities are expected to be feasible on the basis of reasonably available technology; site characterization is expected to provide additional information for planning and design.

frames and hoists, ventilation systems, and a road; and (4) laboratory and field studies.

Standard construction and mining practices can be used to construct the exploratory shaft facility. The secondary egress shaft would be raise-bored, a standard mining technique. No unique or nonstandard techniques are expected to be required for the construction of the support facilities or for the conduct of laboratory or field studies.

The surface characteristics that should be considered in siting are mainly the terrain and the surface drainage; both will be carefully considered in the placement of the exploratory shaft facility, secondary egress shaft, and surface support facilities. The surface facilities, shafts, and access routes to them can be located in generally flat areas with well-established drainage systems. No exceptional ground support methods are expected to be required; wire mesh and rock bolts should provide sufficient ground support to provide for worker safety.

Hydrologic factors that should be considered in siting activities are water availability, potential for flooding especially with regard to sheet flow, and ground-water conditions that could require complex engineering measures beyond those reasonably available. Adequate water supplies are available locally. The design and location of the exploratory shaft and support facilities would include plans for adequate protection from sheet flow, which will result from standard drainage control measures. Because the exploratory shaft facility and the secondary egress shaft would be located in the unsaturated zone and because of the aridity of the surface climate, hydrologic impacts on siting are expected to be minimal.

The tectonic factors to be considered in repository siting include the potential for earthquake-induced ground motion that could require engineering measures beyond reasonably available technology during shaft construction. Reasonably available technology is sufficient to design and construct the surface and underground facilities to withstand the maximum potential ground motion likely to occur at the Yucca Mountain site.

Evaluation for repository construction

Construction activities include (1) the construction of surface and support facilities, including waste-handling and treatment buildings, support buildings, head frames and hoists, a railroad, a road, and utility systems; (2) the construction of underground ventilation filter buildings and underground facilities; and (3) the excavation and stabilization of ramps, shafts, drifts, and emplacement holes (MacDougall, 1985).

Standard construction and mining techniques and practices can be used in most of these construction activities. Waste-handling and treatment facilities, as well as ventilation and filtration systems serving waste-emplacement areas, will be designed and constructed in accordance with applicable specifications followed in other nuclear facilities. Activities requiring nonstandard techniques will be carried out in a manner that provides for the safe handling and processing of potentially hazardous radioactive materials under all foreseeable normal and accident conditions.

The surface characteristics that should be considered in construction activities are mainly the terrain and surface drainage, and both will be carefully considered in the design and placement of surface facilities. The pertinent rock characteristics are the thickness and lateral extent of the host rock; the geomechanical properties of the host rock that affect support requirements; thermomechanical characteristics of the host rock that could affect the ease and safety of waste retrieval, should retrieval become necessary, and other rock characteristics that could compromise the safety of workers. Host-rock characteristics will determine the exact depth selected for the emplacement level, and the exact depth would affect the ease and cost of constructing head frames, hoists and skips, ramps and shafts, and the underground facility. The size and the shape of the emplacement area could also affect the cost of mining the drifts.

The hydrologic factors that should be considered in construction activities are water availability, the potential for flooding from sheet flow, and ground-water conditions that could require complex engineering beyond that reasonably available. Adequate water supplies for repository activities are available locally. The design and locations of surface facilities would include standard drainage control measures to ensure adequate flood protection. The unsaturated condition of the host rock and the aridity of the surface climate both contribute to confidence that hydrologic impacts on construction will be minimal.

The tectonic factors that should be considered in repository construction include the potential for earthquake-induced ground motion. The results of studies to date suggest that the maximum potential ground motion at the site will not require construction methods or practices that are beyond reasonably available technology.

Evaluation for repository operation

Operation activities include waste handling, preparation, and emplacement; administration and management; maintenance; mining; and security. Surface characteristics that may affect operation include those that could cause flooding in the surface or underground facilities, or characteristics that could lead to the failure of engineered components of the repository. No problems with flooding are expected for the surface facilities, and designs will include standard drainage control measures to provide protection for both surface and underground facilities. There are several rock characteristics that could affect repository operation. Among them are the discovery that the host rock is too thin or laterally restricted, or the unexpected occurrence of in situ rock conditions that require special engineering measures such as extensive maintenance of underground openings to guarantee worker safety. The rock characteristics related to thermomechanical response are also important in ensuring that waste retrieval could be accomplished safely and without great cost. All evidence to date suggests that an adequate area of the host rock is available, although it is possible that additional lateral area could be useful for added flexibility. The in situ conditions and thermomechanical properties of the host rock would allow safe operation and retrieval, should retrieval become necessary.

During operation, there are two principal hydrologic concerns: an adequate supply of water must be available, and there should be no ground-water conditions that would require complex technology beyond that which is reasonably available. Adequate water supplies are available locally, and the unsaturated host rock would require no special technology.

The tectonic characteristic of the site that could affect repository operation is the potential for ground motion severe enough to disrupt repository operation, causing injury to personnel, or causing an accidental radiation release. The ground motion that is likely to result from natural seismicity or man-induced seismicity can be estimated and operational procedures can be established to protect workers and facilities. A significant impact on operation would be possible only if earthquakes greatly exceeded the seismic design limits of the facilities; conservative design limits would be used (Section 6.3.3.4).

Evaluation for repository closure

The closure of the repository will consist of backfilling drifts, if required, and sealing shafts, ramps, and boreholes. Surface characteristics would affect shaft and ramp sealing, or backfilling if flooding caused disruption of seals or backfill. The rock characteristics that could affect closure activities or potential retrievability include rock instability in waste-emplacement boreholes or drifts. The potential for thermally induced fracturing or other changes in rock properties could lead to safety problems if retrieval were necessary. Standard drainage control measures are sufficient to guarantee that sealing and backfilling will not be disrupted, and all evidence to date suggests that the retrieval of emplaced wastes should offer no mechanical or safety-related problems.

Hydrologic characteristics would be important in closing the repository if flooding occurred or if water were not available for closure or retrieval operations. Ground-water conditions could affect closure and retrieval if complex engineering measures were required because of unexpected conditions. As previously mentioned, standard drainage control measures would ensure flood protection, and the unsaturated host rock should offer a benign ground-water environment. Tectonic processes could affect closure activities if the earthquake design limits that were imposed were not sufficiently conservative to guarantee the safety of the workers and retrieval of the waste, if necessary. Section 6.3.3.4.5 describes the procedure that will be used to develop conservative seismic design requirements for a repository at Yucca Mountain.

Cost Estimates

On the basis of the available site information and design studies completed to date, preliminary cost estimates have been developed for the repository described in Chapter 5. These estimates were developed as part of the U.S. Department of Energy annual evaluation of the adequacy of the one mil per kilowatt-hour fee for disposal services and do not represent final cost estimates. More definitive estimates will be completed when more detailed designs and site-characterization data become available.

The estimated total life-cycle cost for a repository located in tuff is $8.5 billion (1984 dollars). This includes costs for development and evaluation ($1.5 billion), construction ($1.1 billion), operation ($5.8 billion), and decommissioning ($0.1 billion). The development and evaluation estimate includes costs for site characterization, repository conceptual design, and license application, and technology development. The construction estimate includes costs for repository final procurement and construction design and the construction of all surface facilities and a limited number of underground waste disposal rooms and corridors. The operation estimate includes costs for the construction of the remainder of the underground facilities, the emplacement of the waste underground, and caretaker and backfilling activities. The decommissioning estimate includes costs for shaft sealing and the decontamination and dismantling of the surface facilities.

6.3.4.1.4 Conclusions for the qualifying condition on the ease and cost of siting, construction, operation, and closure guideline

The siting, construction, operation, and closure of a repository at Yucca Mountain are not likely to require special technology and are considered feasible on the basis of existing technology. Site-characterization studies will expand the existing information on host-rock thickness and lateral extent, host-rock mechanical properties, thermo-mechanical properties, the location and characteristics of faults and shear zones, and the subsurface hydrologic system. The currently available repository design information, cost estimates, and design requirements will be updated during ongoing conceptual-design activities. The evidence collected and evaluated to date does not support a finding that the site is not likely to meet the qualifying condition of this preclosure system guideline (level 3).

6.3.5 CONCLUSION REGARDING SUITABILITY OF THE YUCCA MOUNTAIN SITE FOR SITE CHARACTERIZATION

On the basis of the findings stated in the previous discussion of individual guidelines and made in accordance with Appendix III of the siting guidelines (10 CFR 960, 1984), it is concluded that the evidence does not support a finding that the site is disqualified and does not support a finding that the site is not likely to meet the qualifying conditions for ease and cost of siting, construction, operation, and closure. Therefore, it is concluded that the Yucca Mountain site is suitable for site characterization.

6.4 PERFORMANCE ANALYSES

The preceding sections of Chapter 6 have presented guideline-by-guideline analyses of the suitability of the Yucca Mountain site for further characterization. This section describes the preclosure and post-closure performance analyses that support the preclosure system guideline regarding radiological safety and the postclosure system guideline. Other assessments not related to preclosure radiological safety or postclosure performance are not considered here.

6.4.1 PRECLOSURE RADIOLOGICAL SAFETY ASSESSMENTS

The purpose of this section is to describe the approach to the preclosure radiological assessment, to determine whether the assessments are especially sensitive to particular characteristics of the site, and to estimate preclosure performance based on the existing information.

6.4.1.1 Preclosure radiation protection standards

The preclosure system guideline (10 CFR 960.5-1(a)(1), 1984) for radiological safety refers to meeting the applicable safety requirements set forth in 10 CFR Part 60 (1983), 40 CFR 191, Subpart A (1985), and 10 CFR Part 20 (1984). The Subpart A standard requires that the combined annual dose equivalent to any member of the public, from operations covered by 40 CFR Part 190 (1982) and from direct radiation and planned discharges of radioactive materials, not exceed 25 millirem to the whole body, 75 millirem to the thyroid, and 25 millirem to any other organ. The requirements of 10 CFR Part 20 establish limits to exposure of operating personnel, permissible concentrations of radionuclides in air and water for unrestricted areas, and offsite exposure of the general public. The last requirement is that the whole body dose to any member of the public in a year be less than 0.5 rem, with continuous dose limited to 2 millirem per hour or 100 millirem in any 7 consecutive days. This requirement is generally less restrictive than that of 40 CFR 191, Subpart A, but may be limiting under certain short-term conditions.

6.4.1.2 Methods for preclosure radiological assessment

The preclosure performance assessments will include evaluation of potential release and dose and comparison with the requirements of the regulations listed in Section 6.4.1.1. The assessments will consider repository construction and operations including both normal operating conditions and unexpected conditions (i.e., those involving accidental releases).

The specific analysis for each of these conditions will depend upon the designs of the facilities and the waste package. The main purposes of these analyses will be to confirm the acceptability of the designs and to identify mitigative measures to decrease consequences and preventive measures to preclude specific accidents. The analyses may depend on the characteristics of the site and, to the extent that the calculations are particularly sensitive to features of the site, these characteristics would need to be identified and evaluated with regard to preclosure system performance.

6.4.1.2.1 Radiological assessment of construction activities

No radioactive waste would be involved in the construction activities. However, radiation exposure could result from the release of radon from excavated rock and the underground facility. The amount of radon released to the environment depends upon site and engineered system characteristics, including:

1. The amount of natural uranium and thorium in the rock;
2. The characteristics of the rock (e.g., matrix density, porosity) that affect the rate of radon emanation from the rock;
3. The natural and induced thermal fields;
4. The volume and rock surface-area of underground openings;
5. The ventilation flow rate in underground openings, and
6. Other engineered features that are not defined at this stage of the design.

Neutron activation analyses performed on Topopah Spring tuff samples indicate natural uranium content to be in the range of 2.7 to 5.2 parts per million and natural thorium content to be in the range of 22.1 to 25.2 parts per million (Knauss, 1984; Ramspott, 1983). Using these results, the rock bulk density value of 2.12 grams per cubic centimeter (Tillerson and Nimick, 1984), and assuming secular equilibrium of the uranium and thorium series in the Topopah Spring tuff, it is estimated that the radon-220 (thorium series) production is approximately 6 picocuries per cubic centimeter and the radon-222 (uranium series) production is approximately 3 picocuries per cubic centimeters. The concomitant radon emanation rate from the rock, particularly as influenced by the induced thermal load from the emplaced radioactive waste, is not yet known. Although tentative dimensions and ventilation rates for underground openings have been determined, the radionuclide releases and radiation doses due to natural radon have yet to be evaluated.

For present purposes, estimates of radionuclide releases and radiation doses can be based upon data provided for various types of geologic media (DOE, 1980a). These estimates are discussed in Section 5.2.9.1.

These data indicate that excavation of rock roughly corresponding to the disposal of 70,000 metric tons of heavy metal of spent fuel would result in an annual effective whole-body dose for a member of the general population of less than 0.05 millirem. This estimate has been made for excavation of granite, the rock with the highest radon release per unit of excavated rock of those media evaluated in DOE (1980a); the estimate assumes that the release occurs at the point of the excavation. Specific characteristics of the site such as rock type or environmental conditions would not result in greater impacts, because the impact will be mitigated with design features, particularly features of the underground ventilation systems.

6.4.1.2.2 Radiological assessment of normal operations

Neither direct radiation sources nor radionuclide releases during normal operations constitute a significant source of public exposure because of the shielding, packaging, and containment measures that will be taken and because of the large distance that separates the waste from the public. The shielding, packaging, and containment measures needed will be determined when the unit operations have been specified. The greatest potential for radionuclide release during normal operations would occur for the handling of the spent fuel assemblies. Upper bounds to potential impacts can be estimated for possible handling operations and assumptions regarding cladding failure.

A small fraction of the rods may experience cladding failure during reactor operation, or during residence in storage pools. In early designs the fraction of rods that failed during operation was at most 1 percent, but design modifications have reduced this fraction to less than 0.02 percent (Woodley, 1983). There is no evidence of transportation-related cladding failures (DOE, 1978). The fraction that would fail during temporary storage is unknown. If the cladding of any of the rods is ruptured during handling at the site, a portion of the radioactivity in the spent fuel could be released inside the hot cell. High-efficiency particulate air (HEPA) filtration systems can be assumed to remove virtually all (99.9+ percent) of the particulates released from the fuel. For conservatism, virtually all of the tritium, carbon-14, krypton-85 and iodine-129 should be assumed to pass through the system and to be released to the surrounding environment.

Under normal conditions, handling could only result in cladding failure if disassembly of spent fuel elements is performed. For example, up to 0.3 percent of the rods could become stuck in the rod spacers because of swelling in the reactor core (Funk and Jacobson, 1979), and some fraction of these could be ruptured during removal from the spacer with an associated release of the fractions stated above for tritium, carbon-14, krypton-85 and iodine-129.

An estimate of the radionuclide emissions during normal operations can be made from the expected arrival rate of spent fuel rods, frequency of rod failure, radionuclide inventory of the failed rods, and fraction of this inventory that could be released. An upper bound to the release is calculated by assuming an arrival rate of 3,000 metric tons of heavy metal of spent fuel (corresponding to 1,700,000 fuel rods for pressurized-water-reactor fuel) each year, by assuming 0.3 percent of the pins have ruptured and will be stuck in the spacers during disassembly, and by assuming that all of the stuck rods will be ruptured during removal from the spacers. The resulting release fractions are given in Table 6-46. Air concentrations are calculated on the basis of a dispersion factor (X/Q) estimated to be 2×10^{-5} seconds per cubic meter (6×10^{-7} seconds per cubic foot). The calculated concentrations are compared with the concentration limits set by 10 CFR Part 20 (1984) in Table 6-46. Potential exposure can be mitigated by specific facility designs.

Evaluation of committed dose equivalent to compare with regulatory standards will require site-specific information, such as exposure pathway data. However, bounding estimates can be made for simple cases; for example, when the radioactive gases are dispersed in the atmosphere, the whole-body dose equivalent for immersion in the dispersed cloud can be estimated by using site-independent dose factors (ICRP, 1979). For the release in Table 6-46 and a dose conversion factor for krypton-85 of 2×10^{4} (rem per year) per (curies per cubic meter) (ICRP, 1979), the calculated dose equivalent is less than 0.2 millirem per year.

Table 6-46. Assessment of releases from normal preclosure operations

Radionuclide	Inventory[a] (curies)	Fraction released per year[b]	Calculated concentration in air[c] (Ci/m^3)[d]	Concentration limit[e] (Ci/m^3)
Hydrogen-3	9.3×10^5	0.0003	1.8×10^{-10}	2×10^{-7}
Carbon-14	3.7×10^3	0.0003	7.0×10^{-13}	1×10^{-7}
Kyrpton-85	1.5×10^7	0.0009	8.6×10^{-9}	3×10^{-7}
Iodine-129	9.3×10^1	0.0003	1.8×10^{-14}	2×10^{-11}

[a]Based on 3,000 metric tons of heavy metal of 10-year-old spent fuel arriving in a year (DOE, 1979).

[b]Based on 0.3 percent failure of spent fuel rods and fraction of radioactive gases from failed rods released from facility. Regulatory Guide 1.25 (NRC, 1972) indicates that fractions would be 30 percent for krypton-85 and 10 percent for iodine-129. Tritium and carbon-14 are also assumed to be 10 percent.

[c]Based on X/Q = 2×10^{-5} seconds per cubic meter.

[d]Ci/m^3 = curies per cubic meter.

[e]Concentration limits in 10 CFR 20, Appendix B (1984).

6.4.1.2.3 Radiological assessment of accidental releases

The estimates of releases will depend upon the accidents that are plausible at the site. The possible set of accidents to be considered may be altered for specific facility design and operational techniques. A broad spectrum of potential accidents was analyzed by DOE (1979). The most severe of these involved hoist failure during the lowering of the waste disposal container to the repository level. As described in Section 5.1.1.2, however, the reference access method for transferring waste to the underground facility of the prospective Yucca Mountain repository is via a ramp entry. Therefore, the waste-hoist failure would not be a possible event.

As described in Section 5.2.9.2.3, preliminary safety analyses (Jackson et al., 1984) indicate that worst-case accident consequences result from an aircraft impact. For this event, the calculated whole-body equivalent dose to the maximally exposed individual is 68 millirem.

6.4.2 PRELIMINARY ANALYSIS OF POSTCLOSURE PERFORMANCE

This section presents a preliminary performance analysis for the proposed Yucca Mountain waste disposal system. The objective of this preliminary analysis is to estimate the likelihood of satisfying the regulatory requirements contained in the Nuclear Regulatory Commission (NRC) regulations in

10 CFR Part 60 (1983) and the U.S. Environmental Protection Agency (EPA) regulations in 40 CFR Part 191 (1985). The results of the analysis are used in Section 6.3.2 in evaluating the site against the postclosure system guideline (10 CFR 960.4-1, 1984), which is based on these NRC and EPA regulations.

Because of limitations in the data base and analytical methods, this preliminary analysis is not intended to demonstrate compliance with the postclosure performance objectives; rather, it is intended to supplement the evidence that will be used to establish whether the Yucca Mountain site is suitable for site characterization. A full performance assessment to demonstrate compliance with the postclosure performance objective is contingent on site characterization and will follow it.

This section is divided into five parts. Section 6.4.2.1 describes the two major subsystems of the proposed Yucca Mountain waste disposal system. The first of these, the engineered barrier subsystem, is evaluated by an assessment of waste package performance; the second, the natural barrier subsystem, is evaluated at this time by evaluations of ground-water flow and geochemical retardation. The individual performance of each subsystem is analyzed in Section 6.4.2.2, and a preliminary analysis of total system performance is presented in Section 6.4.2.3. Section 6.4.2.4 compares the subsystem and total system performance discussed in earlier sections with the applicable requirements of 10 CFR Part 60 (1983) and 40 CFR Part 191 (1985). The objective of these comparisons is to establish a rough measure of system performance under the conditions expected in the repository; a brief discussion of the effects of disruptive events on system performance is provided in Section 6.4.2.5.

6.4.2.1 Subsystem descriptions

For the purpose of these assessments, it is assumed that a repository at Yucca Mountain would be constructed in the primary area of investigation (Section 6.3.3.2) of roughly 890 hectares (2,200 acres). The underground working areas would be 200 meters (656 feet) or more below the surface in the lower portion of the densely welded Topopah Spring Member (Figure 6-25) of the Paintbrush Tuff. The present repository concept specifies that 616 hectares (1,520 acres) are required for the repository, and mined areas will occupy no more than 25 percent of the total area. It is assumed that the waste will be emplaced as 10-year-old spent fuel and will reach a total of 70,000 metric tons of heavy metal (MTHM) at closure. The radionuclide inventory is given in Table 6-47.

The quantities of radioactive waste and the associated radionuclide inventories that would actually be emplaced in the repository have not yet been established, and the amount of spent fuel emplaced could be less than 70,000 MTHM. Other wastes may be emplaced in the repository in addition to the spent fuel. These other wastes may include high-level wastes currently in storage at West Valley, New York, and defense waste processing facility high-level waste.

These wastes have been explicitly factored into the transportation analyses in Section 5.3. However, the curie inventories of these wastes

Table 6-47. Radionuclide inventory in repository at 360 and 1,060 years after emplacement of 10-year-old spent fuel

Radionuclide	Half-life (years)	Specific activity (Ci/g)[a]	Radionuclide inventory (Ci/1000 MTU)[a]		
			t = 10 yr[b]	t = 360yr[c]	t = 1,060 yr[c]
Cm-246	5.5×10^{3}	2.64×10^{-1}	3.5×10^{1}	3.4×10^{1}	3.1×10^{1}
Cm-245	9.[illegible] $\times 10^{3}$	1.57×10^{-1}	1.8×10^{2}	1.8×10^{2}	1.7×10^{2}
Cm-244	1.76×10^{-1}	8.32×10^{1}	9.0×10^{5}	9.3×10^{-1}	0
Cm-242	4.5×10^{-1}	3.32×10^{3}	8.5×10^{3}	2.6×10^{3}	1.1×10^{2}
Am-243	7.95×10^{3}	1.85×10^{-1}	1.4×10^{4}	1.4×10^{4}	1.3×10^{4}
Am-242	1.52×10^{2}	9.72	1.0×10^{4}	2.6×10^{3}	1.1×10^{2}
Am-241	4.58×10^{2}	3.24	1.6×10^{6}	1.0×10^{6}	3.5×10^{5}
Pu-242	3.79×10^{5}	3.90×10^{-3}	1.6×10^{3}	1.6×10^{3}	1.6×10^{3}
Pu-241	1.32×10^{1}	1.12×10^{2}	6.9×10^{7}	1.8×10^{2}	1.7×10^{2}
Pu-240	6.58×10^{3}	2.26×10^{-1}	4.5×10^{5}	4.4×10^{5}	4.1×10^{5}
Pu-239	2.44×10^{4}	6.13×10^{-2}	2.9×10^{5}	2.9×10^{5}	2.8×10^{5}
Pu-238	8.6×10^{1}	1.75×10^{1}	2.0×10^{6}	2.0×10^{5}	9.3×10^{2}
Np-239	6.4×10^{-3}	2.33×10^{5}	1.4×10^{4}	1.4×10^{4}	1.3×10^{4}
Np-237	2.14×10^{6}	7.05×10^{-4}	3.1×10^{2}	4.4×10^{2}	5.8×10^{2}
U-238	4.51×10^{9}	3.33×10^{-7}	3.2×10^{2}	3.2×10^{2}	3.2×10^{2}
U-236	2.39×10^{7}	6.34×10^{-5}	2.2×10^{2}	2.2×10^{2}	2.3×10^{2}
U-235	7.1×10^{8}	2.14×10^{-6}	1.6×10^{1}	1.6×10^{1}	1.6×10^{1}
U-234	2.47×10^{5}	6.18×10^{-3}	7.4×10^{1}	7.2×10^{2}	7.8×10^{2}
U-233	1.62×10^{5}	9.47×10^{-3}	3.8×10^{-2}	5.3×10^{-1}	2.1
Pa-231	3.25×10^{4}	4.51×10^{-2}	5.3×10^{-3}	1.3×10^{-1}	3.7×10^{-1}
Th-232	1.4×10^{10}	1.10×10^{-7}	1.1×10^{-7}	4.1×10^{-6}	1.2×10^{-5}
Th-230	8.0×10^{4}	1.94×10^{-2}	4.1×10^{-3}	2.2	9.0
Th-229	7.34×10^{3}	2.13×10^{-1}	2.8×10^{-5}	8.0×10^{-3}	9.2×10^{-2}
Ra-226	1.60×10^{3}	9.88×10^{-1}	7.4×10^{-6}	1.2×10^{-1}	1.5
Ra-225	4.05×10^{-2}	3.92×10^{4}	8.1×10^{-5}	8.1×10^{-3}	9.4×10^{-2}
Pb-210	2.23×10^{1}	7.63×10^{1}	7.0×10^{-7}	1.5×10^{-1}	1.7
Cs-137	3.0×10^{1}	8.70×10^{1}	7.5×10^{7}	2.3×10^{4}	2.2×10^{-3}
Cs-135	3.0×10^{6}	8.82×10^{-4}	2.7×10^{2}	2.7×10^{2}	2.7×10^{2}
I-129	1.59×10^{7}	1.74×10^{-4}	3.3×10^{1}	3.3×10^{1}	3.3×10^{1}
Sn-126	1.0×10^{5}	2.84×10^{-2}	4.8×10^{2}	4.8×10^{2}	4.8×10^{2}
Tc-99	2.15×10^{5}	1.70×10^{-2}	1.3×10^{4}	1.3×10^{4}	1.3×10^{4}
Zr-93	9.5×10^{5}	4.04×10^{-3}	1.7×10^{3}	1.7×10^{3}	1.7×10^{3}
Sr-90	2.9×10^{1}	1.37×10^{2}	5.2×10^{7}	1.2×10^{4}	6.5×10^{-4}
Ni-59	8.0×10^{4}	7.57×10^{-2}	3.0×10^{1}	3.0×10^{1}	3.0×10^{1}
C-14	5.73×10^{3}	4.45	8.0×10^{2}	7.4×10^{2}	6.9×10^{2}

[a]MTU = metric tons of uranium; Ci/g = curies per gram.

[b]10 years out of reactor, i.e., the assumed time of emplacement; values taken from tables 3.3.7, 3.3.8, and 3.3.10 of DOE, 1979; once-through-reactor cycle.

[c]300 or 1,000 years after closure, i.e., 360 or 1,060 years out of reactor, assuming a 50-year operations period before closure; values calculated from 10-year inventories and rounded to 2 significant digits.

would constitute less than 1 percent of total repository inventory and would not have a significant incremental impact on repository performance. Therefore, these other wastes are not explicitly evaluated here.

The waste disposal system consists of three major components: (1) the waste package; (2) the mined repository, including any engineered features that are specifically intended to enhance long-term waste containment or isolation; and (3) the geohydrologic and geochemical setting of the site. These three components are described below in terms of their subcomponents that are relevant to postclosure performance.

6.4.2.1.1 Engineered barrier subsystem

The waste package

A reference conceptual design (O'Neal et al., 1984) for a spent fuel waste package is shown in Figure 6-28. The waste disposal container is 70 centimeters (28 inches) in diameter, but its length, including the pintle, may vary from 4.0 to 4.75 meters (13 to 15.6 feet) to accommodate various lengths of fuel rods. The container is fabricated from austenitic stainless steel with a wall thickness of 1 centimeter (0.4 inch). This design will accommodate the fuel rods from 7 pressurized-water-reactor assemblies (3.30 kilowatts) or 14 boiling-water-reactor assemblies (2.66 kilowatts); the fuel rods would be removed from the original assembly hardware and consolidated to fit in the waste disposal containers. The power loadings of 3.30 and 2.66 kilowatts are consistent with a 350°C (662°F) temperature limit imposed to avoid degradation of the Zircaloy cladding around the spent fuel (O'Neal et al., 1984). If it is assumed that the initial thermal loading of the repository is held to 119 kilowatts per hectare (48 kilowatts per acre), then about 18,000 containers would be distributed over 510 hectares (1,260 acres).

The design shown in Figure 6-28 is the least complicated of the selected reference and alternative design configurations for this spent fuel waste package (O'Neal et al., 1984). The waste disposal container would be emplaced in a single vertical borehole, and neither an overpack nor packing material would be used.

Austenitic stainless steel has been chosen as the reference material because of its excellent corrosion and oxidation resistance in environments similar to those anticipated in the Yucca Mountain repository during the containment period. The corrosion and oxidation behavior of one austenitic stainless steel, AISI 304L, has been extensively studied. Test results to date indicate that either uniform corrosion or stress corrosion cracking is the expected failure mode for this material in the dominant environmental conditions in the Yucca Mountain repository. More highly alloyed grades of austenitic stainless steels (AISI 316L and 321) and the related high-nickel austenitic alloy (825) are also being tested as candidate container materials; these alloys are very resistant to localized and stress-assisted forms of corrosion (pitting, crevice, intergranular, stress corrosion cracking, hydrogen embrittlement). Any of these austenitic materials can be used for fabricating the disposal containers illustrated in Figure 6-28. The

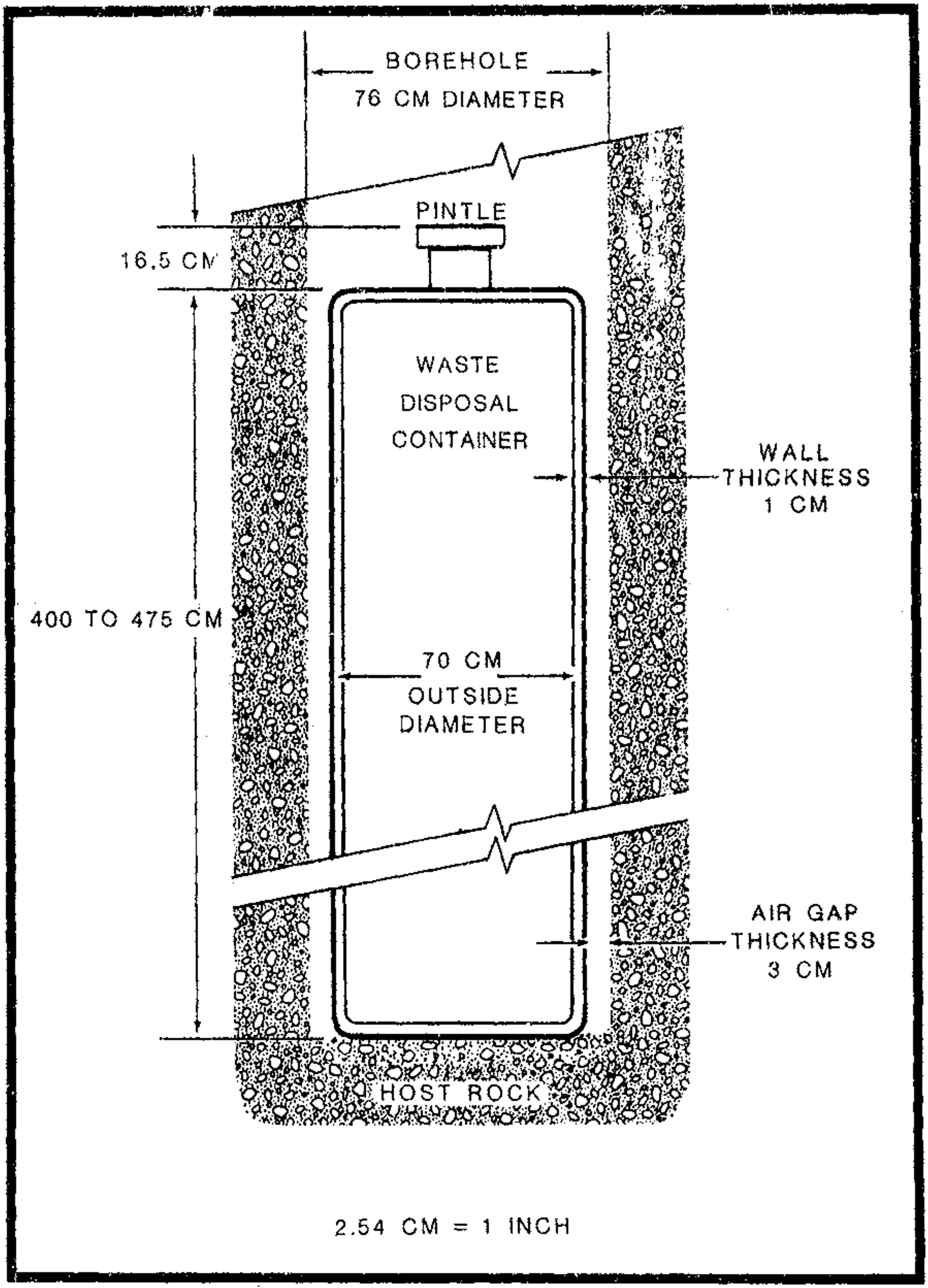

Figure 6-28. Reference conceptual design for spent fuel waste disposal container. From O'Neal et al. (1984).

effects of different fabrication and welding processes on the corrosion and oxidation performance of the container materials are being studied. So far, tests in the expected Yucca Mountain environments have shown no evidence of localized or stress-assisted corrosion. Tests to qualify the candidate container materials are continuing, but because such tests have not demonstrated any failure of 304L by stress corrosion cracking, even under extreme cold-worked, sensitized, and highly stressed conditions, the modeling of containment-barrier lifetime will be based on uniform corrosion, which is known to occur at measureable rates. However, the role of stress corrosion cracking remains a subject of further study.

Copper and copper-base alloys serve as an alternative alloy system to the austenitic materials. Expected corrosion degradation mechanisms and the environmental conditions that cause them are different on copper from those on stainless steel. Alloying additions improve the resistance of copper to corrosion in the expected oxidizing environments. High-purity copper (CDA 102), aluminum bronze (CDA 613), and 70/30 copper-nickel (CDA 715) are being tested. Some modification to the present reference and alternative waste package designs may be needed for copper containers.

The mined repository

By the Nuclear Regulatory Commission (NRC) definition, the engineered barrier consists of the waste package and the underground facility of the repository. These two components combine to provide long-term containment and to control the release of the radioactive material into the geologic setting.

The outer boundary of the mined repository has not yet been clearly defined. The NRC states in 10 CFR Part 60 (1983) that the repository includes the underground structure, underground openings, and backfill materials but excludes shafts, exploratory boreholes, and their seals. For the current calculations, the boundary of the engineered barrier subsystem is defined as a surface coinciding with the walls of the waste-emplacement drifts and emplacement holes.

At present, preliminary hydrologic information and preliminary design data are available to predict the effects of the engineered barrier subsystem on water availability at the waste disposal container. While estimates of the retardation that occurs inside the boundary of the engineered barrier subsystem could be made, the release rate at the accessible environment would not be significantly affected because the major sorptive unit is the tuffaceous beds of Calico Hills, which is some distance below the repository horizon. In future performance analyses, the host rock immediately surrounding the waste disposal containers could be treated either as part of the engineered barrier or the natural barrier subsystem.

6.4.2.1.2 The natural barrier subsystem (the geohydrologic setting)

This preliminary analysis is directed at two components of the natural barrier subsystem: ground-water and geochemical conditions. The most important aspects of these components are (1) the volume and flow of water in the saturated and the unsaturated zones of Yucca Mountain and (2) the geochemical properties of the rocks and waters of Yucca Mountain as they relate to the potential solution, suspension, complexing, and transport of radionuclides by the ground water.

The available information on the flow of water in the saturated and the unsaturated zones of Yucca Mountain is reviewed in Section 6.3.1.1. Briefly, the flow of water occurs in a thick unsaturated section (about 500 to 750 meters, or 1,640 to 2,460 feet thick) and a deep saturated zone. The host rock for the repository is in the unsaturated zone and is characterized by low water content; the repository horizon is generally over 200 meters (656 feet) above the water table.

Water enters the unsaturated zone in the form of precipitation that infiltrates at the land surface and percolates generally vertically downward until it reaches the water table. The flow rate of the percolating water is determined by the rate of infiltration and by the hydraulic properties of the rocks in the unsaturated zone as described in Section 6.3.1.1. On reaching the water table, the ground water then moves in a generally horizontal direction to the accessible environment. It is driven by a hydraulic gradient approximately equal to the slope of the water table and is controlled by the hydraulic properties of the intervening rocks. It is probable that a portion of the ground-water flow in the saturated zone at Yucca Mountain occurs through fractures in the welded units.

The available information on the geochemical properties of the Yucca Mountain site is reviewed in Section 6.3.1.2. Between the repository horizon and the water table, there are several zones containing highly sorptive minerals, particularly zeolites and clays. The formations in the saturated zone also contain varying amounts of clays and zeolites. Because of the sorptive properties of these rocks, dissolved radionuclide-bearing compounds may be transported at effective speeds that are generally less than the local pore-water velocity; this is particularly true if flows are confined to the matrix of the rocks. The reduced speed results in a transport time over the same flow path that is longer than the water-flow time by a number known as the <u>retardation factor</u>, R_f (Equation 6-2). The retardation factor for the jth radionuclide species, $R_f(j)$, is related to the distribution coefficient for the jth species, $K_d(j)$, by the expression (Freeze and Cherry, 1979)

$$R_f(j) = 1 + \frac{\text{bulk density} \times K_d(j)}{\text{porosity}} . \qquad (6\text{-}4)$$

Estimates of distribution coefficients (also known as the sorption ratios, R_d) and retardation factors are listed in Table 6-25 for several waste elements in six of the tuff units that could be crossed by flow in the unsaturated and the saturated zones. These estimates are based on retardation by sorption. Other chemical and physical retardation mechanisms, such as precipitation and matrix diffusion, may increase the effective retardation factor, especially for elements with low sorption ratios. The waste elements with low or zero sorption ratios, hence small retardation factors, are carbon, iodine, and technetium. These few elements will be transported with a speed nearly equal to that of the ground water, unless they are slowed by physical retardation mechanisms or nonsorptive chemical retardation. This possibility is currently under investigation.

6.4.2.2 Preliminary performance analyses of the major components of the system

The performance of each of the three major components of the waste disposal system is evaluated here. The results will be used in Section 6.4.2.3 to establish a reference system configuration and in Section 6.4.2.4 to make comparisons with regulatory performance objectives.

In the remainder of this section, and unless otherwise stated, the use of the term accessible environment is consistent with 40 CFR Part 191 (1985) and means those parts of the lithosphere and atmosphere that lie at a maximum distance of 5 kilometers (3 miles) in any direction from the original location of the radioactive waste.

6.4.2.2.1 The waste package lifetime

For the waste package, the Nuclear Regulatory Commission has provided a performance objective that calls for substantially complete containment of radioactive wastes for 300 to 1,000 years. For purposes of the present analyses, the containment period of the waste package is assumed to be the time during which the waste disposal container is impervious to liquid water. There is, of course, a period of time during which temperatures within and in the vicinity of the containers exceed the boiling point of water, and no liquid water would contact the waste regardless of the integrity of the container; that period of time is not counted in the present analyses. Rather, the lifetime of the reference container is assessed in terms of its resistance to uniform corrosion, the expected failure mode of austenitic stainless steel (see discussion of the waste package in Section 6.4.2.1). Estimates of the uniform corrosion rate for this and other materials have been made based on data from short-term exposure tests that attempt to simulate the Yucca Mountain environment. In addition, there are considerable data in the literature concerning the corrosion properties of 304L stainless steel.

In low-salinity, aerated water with a nearly neutral pH, the uniform-corrosion rate for 304L stainless steel appears to be less than 0.1 mil per year, or about 2.5×10^{-4} centimeter (1.0×10^{-4} inch) per year (Paul and Moran, 1963). If uniform corrosion is the only mechanism that acts to breach the waste disposal container, its lifetime will be about 3,000 years. In contrast to these results, McCright et al. (1983) have observed a maximum rate of 3.7×10^{-5} centimeter (1.5×10^{-5} inch) per year for the uniform corrosion of 304L stainless steel in 2-month exposure tests. In their tests, the sample was immersed under pressure at a temperature of 105°C (221°F) in water from a well in the vicinity of Yucca Mountain (Well J-13) and simultaneously was subjected to a radiation field of 3×10^5 rads per hour. The container lifetime under these conditions would be about 30,000 years. However, McCright et al. (1983) conclude that a conservative upper limit of

1×10^{-4} centimeter (4×10^{-5} inch) per year is reasonable for the uniform corrosion of 304L stainless steel in the Yucca Mountain environment and that the expected container lifetimes are accordingly on the order of 10,000 years.

In summary, the containment period of the waste package could range from 3,000 to 30,000 years if waste disposal container failure through mechanisms other than uniform corrosion can be confidently excluded from consideration. Since sufficient data on the vulnerability of candidate container alloys to failure mechanisms other than uniform corrosion are not yet available, the lower bound on the range of waste package lifetimes, 3,000 years, will be adopted for the analysis of the reference case in Section 6.4.2.3 to achieve some degree of conservatism.

6.4.2.2.2 Release rate from the engineered barrier subsystem

As stated in Section 6.4.2.1, the elements of the repository that would make up the engineered barrier subsystem at the Yucca Mountain site are not yet rigorously defined. To facilitate the present assessments, the inner boundaries of this subsystem are assumed to coincide with the outer boundaries of the waste packages, and the rate of radionuclide release from the engineered barrier subsystem is calculated as the rate of mass transport across the geometrical envelope containing the waste packages.

As long as the uncorroded thickness of the waste disposal container walls was at least a few microns, there could be no significant mass transfer from the interior of the container to its exterior; hence there would be little or no release of nonvolatile, radionuclide-bearing compounds. But, at some time (3,000 to 30,000 years), corrosion or other mechanisms will have attacked the container walls long enough to have produced openings of sufficient size to permit the free passage of water between the interior and exterior; water could then contact the spent fuel rods inside the container. The amount of water that could flow into the container is limited, however. Given the assumed prevailing, downward flux in the rock surrounding the waste emplacement borehole, the discharge of water into the container (and, in steady flow, out of the container) could be no more than FA (in cubic meters per year), where F is the flux (in meters per year) and A is the container area normal to the flux (in square meters). Thus, for an expected flux of less than 0.5 millimeter (0.02 inch) per year ($F = 10^{-3}$ meters per year) and a vertically emplaced reference container ($A = 0.33$ square meter), no more than 0.17 liter (0.04 gallon) of water per year could enter (and exit) the waste disposal container.

Any water that penetrates the waste disposal container could contact the Zircaloy-clad fuel rods. The Zircaloy cladding could offer further protection of the bare spent fuel, but the amount of protection is uncertain, particularly over the long term. Woodley (1983) examined the characteristics of spent fuel from light-water reactors and estimated the cladding failure rate for boiling-water-reactor fuel designs to be between 1.0 percent and a value approaching zero. The lower bound for cladding failures will probably remain near 0.01 to 0.02 percent (Locke, 1975; Garzarolli et al., 1979). In any case, spent fuel cladding will not be 100 percent intact at emplacement.

In the present assessments, any protection offered by the cladding will be ignored. Thus, it is assumed that any water penetrating the container will always contact the bare waste form contained within the Zircaloy cladding, leading to some dissolution of the waste and mass transfer from the waste form to the liquid phase in the form of soluble compounds containing radionuclides.

According to available data, the possible mass-transfer rates from spent fuel to water could vary from essentially zero (for intact Zircaloy-clad fuel rods) to more than 1 part in 100,000 per year for bare fuel elements. The latter rates are, however, extremely unlikely under Yucca Mountain conditions. Wilson and Oversby (1984) report the initial results from tests of spent fuel cladding containment. Solution concentrations indicate a uranium-release rate of 5×10^{-6} per year from bare fuel (pellets from a 13-centimeter (5-inch) long rod segment) submerged in 250 milliliters (6.6×10^{-2} gallon) of deionized water and a release rate of 2×10^{-5} per year for plutonium. These results are similar to release rates measured by Stroes-Gascoyne et al. (1985) in a study of the long-term dissolution of spent fuel in distilled water at 25°C (77°F). Similar studies by Wilson and Oversby (1984) suggest that release rates from spent fuel samples with relatively large artificially induced cladding defects are still 10 to 100 times lower than the release rates from bare fuel. These mass-transfer rates are high enough to suggest that, under the low-flux conditions of Yucca Mountain where water could remain in contact with the waste form for relatively long times, use of a saturation-limited dissolution model is justified. In fact, under saturated conditions in release-rate experiments (Wilson and Oversby, 1984), with high ratios of water volume to waste-form area, solution concentrations appear to reach a steady state in less than 30 days. For the large flux values that would be typical of fracture flow (considered unlikely at Yucca Mountain), solubility kinetics may control the release rate, and a saturation-limited dissolution model would overestimate the rates. Another control on the release rate is the rate at which dissolved compounds at the waste-water interface can diffuse into the flowing water (see Section 6.3.1.2, favorable condition 4). In saturation-limited dissolution, neither kinetics nor diffusion are accounted for, and each unit volume of water that contacts a soluble compound is assumed to attain a solution concentration of that compound no less than S kilograms per cubic meter, where S is the solubility (or solubility limit) of the compound in the solvent under consideration and is a quantity depending on many environmental variables (e.g., temperature, pressure, concentrations of other solute compounds).

The foregoing considerations suggest a way of using the saturation-limited dissolution model to estimate the rate of mass transport across the engineered barrier system. Taking a single waste disposal container (described in Section 6.4.2.1) as the unit of inventory, the rate of mass loss from the engineered barrier owing to dissolution of the spent fuel matrix, $\dot{M}$, should be no more than the expression, $\dot{M} = FAS$, where, to reiterate, F is the flux of water (in cubic meters per square meter per year), A is the container area normal to the flux (in square meters), and S is the solubility limit of the waste matrix (in kilograms per cubic meter). If the upper bound on flux is 0.5 millimeter per year (5×10^{-4} meter per year), A = 0.33 square meter (a vertically emplaced reference container), and $S = 5 \times 10^{-2}$ kilogram per cubic meter, an upper limit on the solubility of uranium dioxide in waters characteristic of Yucca Mountain (Ogard and Kerrisk, 1984), the rate of mass loss is 8.3×10^{-6} kilogram per year. For a container that is assumed to hold 3.3 metric tons of heavy metal, the fractional mass release rate is 2.5×10^{-9} per year. The rate of mass loss in the form of a radionuclide-bearing compound may also be estimated in the same way if S, the solubility limit of the waste matrix, is replaced with the smaller of the two quantities, solubility limit of waste matrix and solubility limit of the radionuclide-bearing compound, and the resulting fractional mass release rate is multiplied by the mass of the radionuclide remaining in the waste disposal container. For those radionuclide species having solubility limits greater than the solubility of the waste matrix, the fractional release rate is seen to be the same as the fractional mass release rate that applies to the total inventory of the container. The solubilities of several waste elements are listed in Table 6-26. With the exception of carbon, cesium, technetium, and iodine (not shown), all solubility values are less than or comparable to the value for uranium oxide.

Flux-dependent rates of mass loss of the type just described will be adopted for the analyses in Section 6.4.2.3; but they are not suitable for making conservative estimates of fractional release rates for purposes of comparing with the Nuclear Regulatory Commission objective for radionuclide releases from the engineered barrier system (generally, no more than one part in 100,000 per year). The rate-of-mass-loss formulation described above does not include mass loss of those solid phases that are not contained in the spent fuel matrix. Oversby and McCright (1984) have described the likely locations and amounts of radionuclides that reside outside of the bare, spent fuel pellet. They postulate that four components of the inventory should be considered in calculating release rates:

1. Radionuclides with releases controlled by matrix dissolution.

2. Radionuclides present in part in the pellet-cladding gap.

3. Radionuclides present in steel spacers and grids.

4. Radionuclides contained in the fuel cladding.

The saturation-limited dissolution models account for component (1), the overwhelming majority of the inventory. The radionuclides of component (2) (cesium, iodine, and possibly technetium) usually amount to less than 1 percent of their total inventory. The high leach rate for cesium-137 observed by Stroes-Gascoyne et al. (1985) in sections of bare spent fuel is probably a consequence of the segregation of a small fraction of the cesium inventory in component (2). In any case, the small fraction of the inventory residing in component (2) can be ignored in calculations of the long-term release at the accessible environment. The most significant radionuclide present in components (3) and (4) is probably the carbon-14 contained in the cladding. In the present analyses, all carbon-14 is assumed to be imbedded in the spent fuel matrix.

Ground-water travel times

Estimates of ground-water travel time from the repository to the accessible environment will be needed for the analyses in Section 6.4.2.3. These estimates are directly taken from the arguments in Section 6.3.1.1.5 that use various lines of reasoning and evidence to show that (1) 0.5 millimeter (0.02 inch) per year is a reasonable and conservative upper bound on flux to use in calculating unsaturated zone, pre-waste-emplacement travel time; (2) flux below the repository horizon can be regarded as vertical and faults are not known to be continuous pathways from the repository to the water table; and (3) travel times between a point 50 meters (160 feet) below the centerline of the repository and the water table take on a distribution of values (at 0.5 millimeter (0.02 inch) per year, the mean travel time is 43,405 years with a standard deviation of 12,800 years) The travel times through the saturated zone to the accessible environment 5 kilometers (3 miles) from the margin of the repository were also estimated in Section 6.3.1.1.5 but will not be taken into account in the calculations of Section 6.4.2.3.

As explained in Section 6.3.1.1.5, a distribution of ground-water travel times is obtained when one takes into account the variable thicknesses of the rock units and the natural variability of hydraulic properties (e.g., effective porosity, saturated matrix conductivity) within each unit. The distribution of ground-water travel times may also be interpreted as the probability that a nonretarded contaminant particle, which is released at a randomly selected point in the repository, will reach the accessible environment in a specified time interval following release. The use of such distributions of ground-water travel times in the calculations of the release of nonretarded, radionuclide-bearing compounds in Section 6.4.2.3. improves the realism of such calculations, since part of the effects of hydrodynamic dispersion can be included (Freeze and Cherry, 1979).

Reference retardation factors

Point estimates of porous-flow retardation factors in the welded and the nonwelded tuff units will also be needed for the analyses in Section 6.4.2.3. These estimates are shown in Table 6-48; they are consistent with the geochemical properties of the tuffs at Yucca Mountain described in Section 6.3.1.2, although the estimates of retardation factors were based on different rock densities and hydrologic parameters. To be consistent with the theory of flow in partially saturated porous media, moisture contents were used in the formula for R_f given in Section 6.4.2.1.2 in place of porosity to generate the estimates of the retardation factors in Table 6-48. Also, bulk densities of 2.33 and 1.48 grams per cubic centimeter were assigned to welded and nonwelded tuff, respectively based on Scott et al. (1983); these values of bulk density are different from the value (2.5 grams per cubic centimeter) assumed in Table 6-25. A comparison of the two tables, 6-48 and 6-25, shows that the resulting differences in retardation factors are not large and, as will be demonstrated in Section 6.4.2.3, are not essential to the present analysis. The largest source of uncertainty in the retardation factor is the distribution coefficient, which may vary by factors of 10 or even 100 (Daniels et al., 1982), though it is unlikely that the spatially averaged distribution coefficients could be overestimated by factors of 100. The estimates given in Table 6-25 are believed to represent spatial averages.

A study of Table 6-48 reveals that all important radionuclide-bearing compounds, except those containing carbon, iodine, or technetium, have

Table 6-48. Distribution coefficients (sorption ratios) and calculated retardation factors used in preliminary system performance analyses--reference case

Element	Distribution coefficient,[a] K_d (ml/g)		Retardation factor,[b] $R_f(j)$	
	Welded	Nonwelded	Welded	Nonwelded
Americium (Am)	1,200	4,600	8,000	24,000
Carbon (C)	0[c]	0[c]	1	1
Curium (Cm)	1,200	4,600	28,000	24,000
Cesium (Cs)	290	7,800	6,700	41,000
Iodine (I)	0[c]	0[c]	1	1
Neptunium (Np)	7	11	160	58
Protactinium (Pa)	64	140	1,500	740
Lead (Pb)	5[d]	5[d]	120	27
Plutonium (Pu)	64	140	1,500	740
Radium (Ra)	25,000[e]	25,000[e]	580,000	130,000
Tin (Sn)	100[d]	100[d]	2,300	530
Strontium (Sr)	53	3,900	1,200	21,000
Technetium (Tc)	0.3	0[c]	8	1
Thorium (Th)	500[d]	500[d]	12,000	2,600
Uranium (U)	1.8	5.3	27	45
Zirconium (Zr)	500[d]	500[d]	12,000	2,600

[a] Unless otherwise indicated, distribution coefficients (sorption ratios) were taken from Table 6-25 or were inferred from the sorption ratios quoted by Daniels et al. (1982); ml/g = milliliters per gram.

[b] Calculated using values of moisture content of 10 and 28 percent and bulk densities of 2.33 and 1.48 grams per cubic centimeter for welded and nonwelded tuff.

[c] No data available; assumed to be zero.

[d] Inferred from the mid-range retardation factor for tuffs in compilation in Table 7-1 in National Research Council (1983).

[e] Barium used as a chemical analog.

retardation factors greater than 10. Consequently, carbon, iodine, and technetium can be reasonably assumed to have transport-time distributions identical with the water travel-time distributions described in Section 6.3.1.1.5, whereas the transport-time distributions for the dissolved compounds bearing the other radionuclides species are expected to be the water travel-time distribution uniformly shifted to larger times by a factor approximately equal to the average retardation factor for the combination of rock units crossed by the flow. The latter expectation has been tested for uranium using the retardation factors shown in Table 6-8 and the numerical simulation of ground-water travel described in Section 6 3.1.1.5; the sample mean of the transport-time distribution for uranium was 452,303 years, and the standard deviation was 77,115 years. This result suggests that cumulative releases of uranium (and also any radionuclide with a retardation factor greater than that for uranium) would be miniscule, even over a 100,000-year period, and that all species except carbon, iodine, and technetium can be ignored in the calculations of release to the accessible environment that will be presented in the following section.

6.4.2.3 Preliminary system performance analysis

The purpose of this section is to provide information for the preliminary evaluation of the Yucca Mountain site against the postclosure system guideline (Section 6.3.2). The purpose is accomplished by using simple methods, available information, and the results of the preliminary subsystem performance analyses in Section 6.4.2.2 to estimate the performance of the total system. The measure of total system performance will be given by the cumulative curies released to the accessible environment in the form of the jth radionuclide up to time t after repository closure. Times beyond 100,000 years after closure are not considered in these analyses.

6.4.2.3.1 System description

A simple conceptual model of the proposed waste disposal system at Yucca Mountain is shown in Figure 6-29. The level of detail in this conceptual model is consistent with the present knowledge of the natural and the engineered barrier subsystems, as well as the information available on the components of the waste disposal system (i.e., the waste package, the mined repository, and the geologic setting). The mathematical relationships used to quantify the conceptual model of the total system in these preliminary analyses are consistent with the level of detail in that conceptual model.

The waste package and the mined-repository components described in Section 6.4.2.1 are contained in the "repository" shown in Figure 6-29. The waste packages are assumed to be uniformly distributed throughout the repository. The radioactivity-release rate $\dot{C}_j$ in curies per year from each waste package is given by

$$\dot{C}_j = a_j f_j(t)\dot{M} \qquad (6\text{-}5)$$

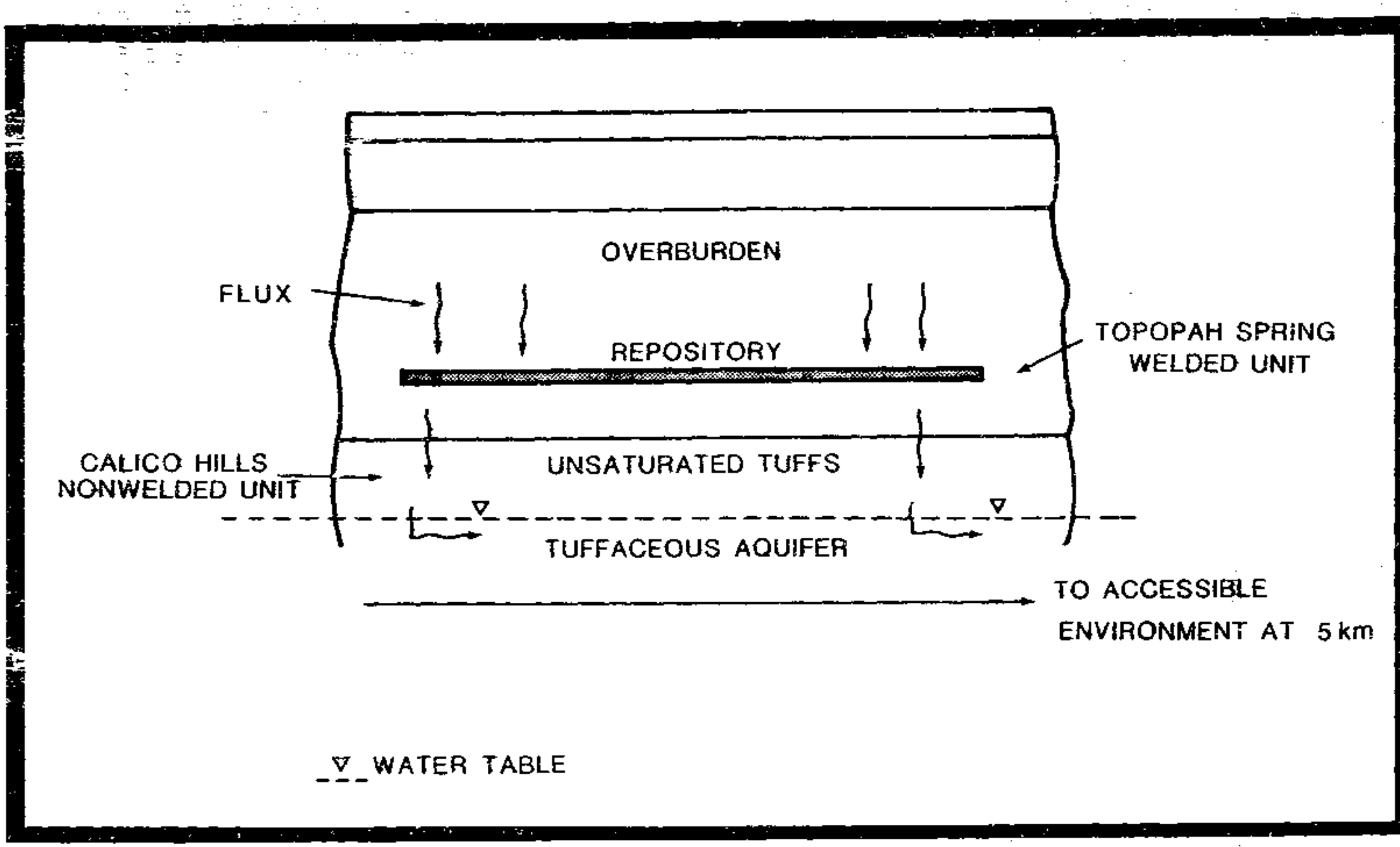

Figure 6-29. A simple model of proposed waste-disposal system at Yucca Mountain.

where a_j is the specific activity for the jth radionuclide and $f_j(t)$ is the fraction of the inventory mass that remains at time t in the form of the jth radionuclide. The quantity $\dot{M}$ is the mass release rate from the engineered barrier subsystem described in Section 6.4.2.2. Note that the releases of the small fraction of the inventory contained in the pellet-cladding gaps are ignored. The total radioactivity release rate from the engineered barrier subsystem to percolating ground water is simply the release rate from a single waste package times the number of waste packages. In effect, the repository is treated as a planar source term for solutes injected into the unsaturated zone flux.

Water flow through the overburden and the unsaturated tuffs below the repository is assumed to be uniform and downward; the flux is treated as a model parameter that applies only at or below the level of the repository. Flow in the unsaturated zone is as described in sections 6.3.1.1.5 and 6.4.2.2.2. The water flow time in the saturated zone has been ignored because adding the saturated travel time makes little difference in the total travel time, although retardation in the saturated zone would be expected to delay radionuclide transport.

The calculational model used to estimate the transport of radionuclide-bearing compounds from the disturbed zone through the unsaturated tuffs and to the water table is a modification of the model that was used to calculate releases in the draft version of this document. In brief, the model is basically the analytic solution to the one-dimensional dispersionless transport equation for a single-member decay chain (for example, see Harada et al., 1980) with Equation 6-5 representing the time-dependent initial conditions on radionuclide release at the repository level. The analytic solution gives the cumulative, total discharge to the water table (in curies) of one of the three nonretarded species, carbon, iodine, and technetium, as a function of time since closure and of travel time (which is treated as an independent variable in this formulation). The distributions of travel times obtained in Section 6.3.1.1.5 are then used to calculate the expected cumulative discharge of each of the three nonretarded radionuclides up to 10,000 and 100,000 years after closure by integrating the product of the analytic solution and the travel-time distribution over all travel times. For the sake of analytical simplicity, the travel-time distribution is assumed to be normal in these calculations with mean travel times and standard deviations given by the sample means and standard deviations obtained in the numerical simulations of Section 6.3.1.1.5. However, an inspection of the empirical distributions obtained in Section 6.3.1.1.5 show that the travel-time distribution accounting for all travel-times from the disturbed zone to the water table is not a normal distribution; it is skewed towards longer travel times more than would be expected for a normal distribution (see Figure 6-7). The effect of the normal-distribution approximation on the results of this evaluation is therefore to overestimate the curies released to the water table over 10,000 years and slightly underestimate curies released over 100,000 years. The reader is cautioned that this simple calculational model has not been benchmarked or validated, but it has been shown to produce results that agree with more conventional solutions to radionuclide-transport problems.

In the remainder of this section, the performance of the system in two configurations will be calculated with the simple conceptual model just described. The two configurations are as follows:

1. Reference configuration: The reference configuration for the total system is intended to represent conservative estimates of values and conditions that can be supported by the analyses of subsystem and component performance in Section 6.4.2.2. The reference values and conditions developed in Section 6.4.2.2 are collected and summarized in Table 6-49.

2. Performance limits configuration: The performance-limits configuration is the same as the reference case except that the waste package lifetime is limited to 300 years and the fractional release rate from the engineered-barrier subsystem is varied about 1×10^{-5} per year, the upper limit on fractional release rates defined in 10 CFR 60.113 (1983).

6.4.2.3.2 System analysis

The estimated radioactivity releases to the accessible environment by the model system in the two configurations are listed in Table 6-50. For the reference configuration (upper bound flux value of 0.5 millimeters (0.02 inch) per year), the fractional release rates were assumed to be proportional to the flux, and to occur according to the simple model of the rate of release from the engineered barrier subsystem (Section 6.4.2.2).

For the performance-limits configuration, calculations were made for three values of the release rate that were varied about 1×10^{-5} per year (i.e., 10^{-6} to 10^{-4}); the flux in the performance-limits configuration is arbitrarily set at the upper bound of current flux estimates, 0.5 millimeter (0.02 inch) per year, which corresponds to a physically defensible release rate of about 2.5×10^{-9} per year (Section 6.4.2.2). In order to achieve release rates of 10^{-6} to 10^{-4} per year at this flux, the solubility of the uranium oxide matrix would have to be 100 to 10,000 times larger than the largest value (about 5×10^{-2} kilogram per cubic meter) applying to Yucca Mountain waters (Ogard and Kerrisk, 1984). Such a circumstance is clearly not credible. Fractional release rates briefly exceeding 10^{-4} per year are theoretically possible for the less than 1 percent of the inventories of cesium, iodine, and possibly technetium that are believed to reside in the pellet-cladding gaps of the spent fuel (see Section 6.4.2.2.2), but the average fractional release rate for these components will probably be bounded by the unknown failure rate of the Zircaloy cladding. In any case such sporadic release of less than 1 percent of the inventories of cesium and iodine would have little effect on the releases to the water table indicated under the performance-limits case in Table 6-50.

6.4.2.4 Comparisons with regulatory performance objectives

In this section, the results of the preliminary subsystem performance analyses, Section 6.4.2.2, and the preliminary system performance analyses, Section 6.4.2.3, are compared with applicable regulatory performance objectives. The comparisons are not intended to definitively show that the performance of the subsystems and the total system will meet applicable

Table 6-49. Summary of values and conditions used in preliminary system performance analysis

Item	Reference case (upper bound flux value)	Uncertainty[a]
Waste package lifetime	3,000 yr	3,000 to 30,000 yr
Fractional release rate from engineered barrier subsystem[b]	2.5×10^{-9} per yr	0 to 2×10^{-9} per yr
Flux through repository level	0.5 mm/yr[c]	1×10^{-7} to 0.5 mm/yr
Expected water-flow times between disturbed zone[d] and water table	43,270 yr	30,470 to 56,070[e]
Retardation factors for unsaturated tuffs	(see Table 6-48)	Consistent with as much as 15 times more or less than Table 6-48 values for distribution coefficients[f]

[a]Range of uncertainties in the analyses of components (Section 6.4.2.2).
[b]See Section 6.4.2.2; release rate depends on flux; spent fuel dissolution only (for vertical emplacement).
[c]Section 6.3.1.1 reports a matrix flux of less than 0.5 millimeter (0.02 inch) per year.
[d]Disturbed zone is assumed to be approximately 50 meters (160 feet) below center plane of repository; see Section 6.3.1.1.5.
[e]These numbers are means of ground-water travel time distributions; full distributions were used in actual calculations.
[f]Data from Daniels et al. (1982).

regulations. Rather, the regulatory criteria are used to detect areas that require increased study or emphasis. The comparisons may also increase or decrease levels of confidence in the ability of the subsystems and the total system to eventually meet the regulatory performance objectives.

The comparisons are presented in Table 6-51, which lists some of the applicable regulatory criteria, briefly summarizes their content, and presents the relevant findings of sections 6.4.2.2 and 6.4.2.3. Several cautions are warranted: with respect to 40 CFR 191.13 and 191.16 (1985) (items 1 and 3), the likelihood of exceeding the stated release limits is not addressed by the analyses of Section 6.4.2.3, and both the conceptual and

Table 6-50. Preliminary estimates of cumulative radioactivity released to the accessible environment from a repository containing 70,000 metric tons of heavy metal

Release rate per year	Cumulative radioactivity (curies) 10,000 years[a]	Cumulative radioactivity (curies) 100,000 years[b]	Isotope released
	REFERENCE CASE[c] (upper bound flux of 0.5 millimeter per year)		
(d)	0	1.4×10^{-2}	C-14
(d)	0	0.3	I-129
(d)	0	97	Tc-99
	PERFORMANCE-LIMITS CASE[e] (not considered possible at Yucca Mountain)		
1×10^{-6}	0	2.8×10^{-1}	C-14
		6.2	I-129
		1.9×10^{3}	Tc-99
1×10^{-5}	0	2.8	C-14
		6.1×10^{1}	I-129
		1.9×10^{4}	Tc-99
1×10^{-4}	0	2.7×10^{1}	C-14
		5.4×10^{2}	I-129
		1.7×10^{5}	Tc-99

[a]The ground-water travel-time distributions calculated in Section 6.3.1.1.5 show a negligible but nonzero probability of travel times less than 10,000 years. Accordingly, the calculations of curies released to the accessible environment in Section 6.4.2.3.2 predict releases by 10,000 years that are not exactly zero, but are tiny fractions of the releases permitted by the EPA regulation: for the reference case (upper bound flux value), the curies released in 10,000 years are less than 0.00001 percent of permitted releases; for the three artificial release rates of the performance-limits case, 1×10^{-6}, 1×10^{-5}, and 1×10^{-4} per year, the curies released are respectively less than 0.0002 percent, 0.002 percent, and 0.02 percent of the permitted releases.

[b]Note that all cumulative radioactivity values at 100,000 years are below the releases permitted for 10,000 years by 40 CFR Part 191 (1985).

[c]See Table 6-49 text for other parameter values.

[d] Fractional release rate is 2.5×10^{-9} per year.

[e] Release rate artificially varied; flux maintained at an upper bound of 0.5 millimeter (0.02 inch) per year.

Table 6-51. Comparison of regulatory criteria and the results of preliminary system performance analyses for a repository at Yucca Mountain

Regulatory criterion	Relevant stipulation	Predicted system performance
40 CFR 191.13 containment requirements	"...cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal from all significant processes and events..." shall have a likelihood of less than 1 chance in 10 of exceeding the quantities calculated according to Table 1 (Appendix A).	Expected releases of radionuclides to accessible environment for 100,000 years do not exceed release limits specified for 10,000 years (Table 6-50).
40 CFR 191.15 individual protection requirements	"...for 1,000 years after disposal. Undisturbed performance of the disposal system shall not cause the annual dose equivalent from the disposal system to any member of the public in the accessible environment to exceed 25 millirems to the whole body or 75 millirems to any critical organ."	Waste package lifetime is expected to greatly exceed 1,000 years; radiation that could affect members of the public would be totally confined over this period (Section 6.4.2.2.1).
40 CFR 191.16 ground-water protection requirements	"...for 1,000 years after disposal, undisturbed performance of the disposal system shall not cause the radionuclide concentrations averaged over any year in water withdrawn from any portion of a special source of ground water to exceed: (1) 5 picocuries per liter of radium-226 and radium-228; (2) 15 picocuries per liter of alpha-emitting radionuclides (including radium-226 and radium-228 but excluding radon); or..."	Waste package lifetime is expected to greatly exceed 1,000 years; soluble radionuclides that could enter ground waters would be totally confined over this period (Section 6.4.2.2.1).

Table 6-51. Comparison of regulatory criteria and the results of preliminary system performance analyses for a repository at Yucca Mountain (continued)

Regulatory criterion	Relevant stipulation	Predicted system performance
10 CFR 60.113 ground-water travel time requirements	Pre-waste-emplacement ground-water travel time shall be at least 1,000 years.	Ground-water travel time to accessible environment is expected to exceed 43,000 years (Section 6.3.1.1).
10 CFR 60.113 waste package containment requirement	Containment of radioactive waste within the waste packages will be substantially complete for a period to be determined by the NRC, but such a period shall not be less than 300 years nor more than 1,000 years after permanent closure of the geologic repository.	Expected waste package lifetime in the Yucca Mountain environment is 3,000 years or more (Section 6.4.2.3).
10 CFR 60.113 long-term release requirement for engineered barrier system	The release rate of any radionuclide from the engineered barrier system following the containment period shall not exceed 1 part in 100,000 per year of the inventory present 1,000 years after closure.	Time-averaged fractional-release rates are expected to be much lower in the Yucca Mountain environment than 1 part in 100,000 per year (Section 6.4.2.3).

mathematical models used in the analyses are oversimplified. With respect to the 10 CFR 60.113 (1983) requirements for the waste package lifetime (item 4), it could be argued that uniform corrosion and stress-corrosion cracking would not be the only mechanisms that contribute to waste disposal container degradation in the Yucca Mountain environment. Other mechanisms could involve the structural failure of the containers because of instability of the surrounding rock. A statistical model of container breaching needs to be developed; such a model would necessarily predict some small release well before the mean lifetime of the container has elapsed. This issue also relates to the release rate of radionuclides after the containment period (item 5). The actual mass-transfer rate appears to be proportional to the area of the waste form exposed to flowing water through breaches in the Zircaloy cladding. The wetted area of waste within the container probably would not increase abruptly, as postulated in the system analyses, but would increase slowly and in a random fashion as time elapsed.

The analysis of system performance in Section 6.4.2.3 represents the performance of the undisturbed waste disposal system. Uncertainties in predicted system behavior were not evaluated, and the possibility that the waste disposal system could be disrupted by unlikely natural events or intentional human intrusion was not considered. These preliminary assessments were performed with limited data and very simple conceptual models.

The preliminary analyses indicate that site characterization activities and studies could profitably focus on the following key uncertainties:

1. Conceptual hydrologic models of flow in the unsaturated zone at Yucca Mountain.

2. The expected physical and chemical environment in the repository for 10,000 years after closure.

3. The conditional waste disposal container lifetime distributions in the postclosure repository environment.

In addition, these and other assessments (e.g., Sinnock et al., 1984) suggest that refinements in the theory of flow and transport in fractured, porous unsaturated rock will be needed before adequate postcharacterization assessments can be made. In particular, methods for treating the stochastic aspects of flow and transport in fractured, porous media need to be developed in order to estimate the effects of hydrodynamic dispersion and chemical retardation on potential radionuclide releases to the accessible environment. A data base containing estimates of the mean values and other statistical quantities for key rock properties is also essential.

6.4.2.5 Preliminary evaluation of disruptive events

The evaluations of the Yucca Mountain site against the postclosure technical guidelines (Section 6.3.1) contain assessments of the effects of many potentially disruptive natural processes on a repository at Yucca Mountain.

Some of the relevant assessments in that section are summarized in this section, which ends with a discussion of the likelihood and consequences of human intrusion after closure.

6.4.2.5.1 Disruptive natural processes

Fracture flow

Travel time calculations in the unsaturated zone, presented in Section 6.3.1.1.5 (Geohydrology), include fracture flow in intervals where the flux of 0.5 millimeter (0.02 inch) per year is greater than the saturated matrix hydraulic conductivity. However, no continuous fracture pathway from the disturbed zone to the water table is included in the calculations. Although the formation of new fractures is considered unlikely because of the highly fractured nature of the potential host rock, one of the disruptive scenarios that will be considered is that of the formation of a new structural feature that could conduct steady hydrologic flow.

A qualitative consequence assessment of such a feature indicates that even in the most extreme case where the feature with steady flow develops instantaneously after repository closure, there is likely to be no release to the accessible environment through the water pathway in the next 10,000 years. Although very rapid transport of any dissolved waste would be possible through the unsaturated zone, travel times in the saturated zone are reported to be at least 140 years under current flux conditions and very conservative assumptions (Section 6.3.1.1.5). Conservative retardation factors (see Section 6.3.1.2.3), which are based on the effectiveness of matrix diffusion in the saturated zone, indicate that radionuclide travel times are likely to be at least 100 times slower than water travel times. This indicates that under current flux conditions, the saturated zone offers a significant protective barrier that will retard radionuclide transport so that U.S. Environmental Protection Agency (EPA) release limits are not likely to be exceeded at the accessible environment under even the most extreme scenarios.

Climatic changes

Under the most extreme climatic changes considered possible at Yucca Mountain during the next 10,000 years, an estimated 100 percent increase in precipitation during a full pluvial could increase recharge by as much as 15 times the present value of 0.5 millimeter (0.02 inch) per year (see Section 6.3.1.4.4 for complete discussion). It should be noted that this scenario is highly conservative and may be unrealistic because as much as two-thirds of the increased precipitation may become runoff rather than recharge. Increased precipitation is likely to cause increased flux and a possible increase in the elevation of the water table beneath the primary repository area. The potential effects of increased water-table altitude are discussed in Section 6.3.1.4.4, where it is explained that even under the maximum position of the water table, a sufficient thickness of unsaturated zone will remain between the repository and the water table to maintain isolation. In addition the protection from unacceptable radionuclide releases that is offered by the saturated zone will be effective. As summarized under the fracture flow discussion above, the travel time for radionuclides in the saturated zone is expected to be at least 100 times slower than the travel time for water. This provides increased confidence that even under the most extreme, low probability scenarios of a return to full pluvial conditions very soon after repository closure, releases to the accessible environment in 10,000 years are not likely to exceed the EPA release limits.

Extreme erosion

Erosion (Section 6.3.1.5) has proceeded at Yucca Mountain at a rate of less than 1×10^{-4} meter (3.3×10^{-4} foot) per year for the past 300,000 years. Using this rate gives 2.3 million years for the time required to remove the minimum repository overburden of 230 meters (750 feet). Consequently, erosion without major vertical tectonic movement is not a credible disruptive process at Yucca Mountain.

Dissolution

Dissolution (Section 6.3.1.6) of the host rock is not credible at Yucca Mountain. The silica-rich tuffaceous rocks are insoluble under present and expected physical and chemical conditions.

Effects of tectonism

Possible consequences of tectonism were considered in Section 6.3.1.7 (Tectonics), but none are likely to affect waste isolation: faulting is not expected to create new ground-water pathways to the accessible environment or to significantly lower the isolation potential of Yucca Mountain; the occurrence of basaltic eruptions at the site is considered unlikely, and other changes related to such activity are even more unlikely. Although the region surrounding Yucca Mountain has been tectonically active during the Quaternary Period, there is no evidence of extreme activity at Yucca Mountain. The largest historic earthquake within the geologic setting is reported in Section 6.3.1.7 to be a $M = 6$ located about 110 kilometers (68 miles) southwest of the site. Recurrence intervals within the region are reported to be on the order of 25,000 years for $M \geq 7$ earthquakes, 2,500 years for $M \geq 6$ earthquakes, and 250 years for $M \geq 5$ earthquakes. The potential effects of earthquakes on containment and isolation will be evaluated; qualitative assessments suggest that ground motion associated with earthquakes is unlikely to cause disruption of emplaced waste disposal containers. Displacement associated with very large earthquakes could disrupt containers. However, under current flux conditions, insufficient water is available to dissolve and transport wastes in quantities that would exceed release limits at the accessible environment (see Section 6.4.2.3.2). A further barrier is offered by the retardation that is expected in the saturated zone, as discussed above under fracture flow and climate changes. Regarding basaltic eruptions at the site, Crowe et al. (1982) estimate that the cumulative probability that such events will disrupt the site within the next 10,000 years is between 4.7×10^{-4} and 3.3×10^{-6}. All these estimates lie near the probability limits beyond which disruptive events can be classified as not credible.

Human intrusion

Section 6.3.1.8 (Human interference and natural resources) concluded that there would be little incentive for resource exploration of the Yucca Mountain site in the near future. There are no known natural resources that have or are projected to have in the foreseeable future a value great enough to be considered a commercially extractable resource. Thus, as long as some records of resource distribution are available, it is highly unlikely that people will mine or drill at Yucca Mountain.

Limited water resources are present but are not expected to be amenable to exploitation under current or future economic standards and needs. It should be noted that the most likely result of excessive ground-water extraction near the Yucca Mountain site is an increase in the thickness of the unsaturated zone. Thus, in the unlikely event that these water resources are exploited by future generations, the resulting increase in the thickness of the unsaturated zone would improve the isolation potential of the site.

The population density in the area surrounding the Yucca Mountain site is very low (See Section 6.2.1.2). The rugged terrain, arid climate, lack of surface water, and the deep ground-water table in the area are likely to persist in the future and to continue to limit the population density in the immediate vicinity of Yucca Mountain. Therefore, scenarios for human instrusion which involve exploratory drilling that accidently penetrates a waste container are likely to have very small population effects. In addition, exploratory drilling in the unsaturated zone does not necessarily lead to increased radioactive releases along water pathways. The regulations addressing such human intrusion scenarios (40 CFR 191, Appendix B (1985)) indicate that direct release of ground water from the repository horizon due to natural flow or pumping, and the creation of a high permeability flow path should be considered as the two most severe consequences of such exploratory drilling. With the absence of ground water and the very low expected flux (See Section 6.3.1.1.5), neither of these scenarios are plausible for an unsaturated zone repository. Thus, the only potential radiation exposure would be to the drilling crew due to contact with extracted waste container contents. It may be reasonable to assume that availability of drilling technology would be accompanied by the ability to detect hazardous material, as is suggested in 40 CFR 191, Appendix B (1985). Additionally, the probability of directly penetrating a waste container is considered to be very low, since it involves the compound probability of drilling into the repository <u>and</u> the probability of directly striking a waste container. Consequently, human intrusion does not appear to be a significant disruptive process at Yucca Mountain.

6.4.2.6 Conclusion

The foregoing preliminary performance analyses uncovered no information that indicates that the Yucca Mountain site is unsuitable for further characterization or that it is likely to be disqualified under the postclosure system guideline (Section 6.3.2) after site characterization and more refined analyses of system performance.

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Chapter 7

COMPARATIVE EVALUATION OF NOMINATED SITES

7.1 INTRODUCTION

7.1.1 PURPOSE AND REQUIREMENTS

This chapter presents a comparative evaluation of the five sites nominated as suitable for site characterization: Davis Canyon, Deaf Smith County, Hanford, Richton Dome, and Yucca Mountain (see Figure 7-1). Each site is a preferred site within a geohydrologic setting: Davis Canyon is in the bedded salt of the Paradox Basin in Utah; Deaf Smith County is in the bedded salt of the Permian Basin in Texas; Hanford is in basalt in the Columbia Plateau in Washington; Richton is a salt dome in Mississippi; and Yucca Mountain is in tuff in the Southern Great Basin in Nevada. The process that led to the identification of these sites is described in Chapter 2.

The major objective of this chapter is to present a comparative evaluation of the sites proposed for nomination in order to satisfy the following requirements:

1. Section 112(b)(E)(iv) of the Nuclear Waste Policy Act of 1982 (the Act), which requires that a "reasonable comparative evaluation" be included in the environmental assessments that accompany site nomination.

2. Section 960.3-2-2-3 of DOE's siting guidelines (10 CFR Part 960), which requires that a reasonable comparative evaluation be made and that a summary of evaluations with respect to the qualifying condition for each guideline be provided to "allow comparisons to be made among sites on the basis of each guideline."

This comparative evaluation is intended to facilitate the comparison of the more-detailed suitability evaluations reported for each site in Chapter 6. The comparison should assist the reader in understanding the basis for the nomination of five sites as suitable for characterization (Section 112(b)(1)(A) of the Act); it is not intended to directly support the subsequent recommendation of three sites for characterization as candidate sites.

7.1.2 APPROACH AND ORGANIZATION

This comparative evaluation of the five nominated sites is based on the postclosure and the preclosure guidelines (10 CFR Part 960, Subparts B and C, respectively). The reader is referred to Chapter 6 for a detailed discussion of the structure and the content of the siting guidelines. The evaluation presented in this chapter includes both the system guidelines and the technical guidelines.

Figure 7-1. Sites selected for nomination.

The comparison of the sites against each technical guideline uses the information from the guideline evaluations presented in Chapter 6 of the five environmental assessments, whereas the comparisons against the system guidelines summarize directly the evaluations reported in Chapter 6. The approach used to compare the sites against each technical guideline is summarized below.

In order to facilitate the comparison of sites on the basis of each qualifying condition, major considerations were derived by identifying the favorable, potentially adverse, and disqualifying conditions that deal with the same general topic. Contributing factors representing site characteristics that are potentially important to each major consideration were also identified. The relative importance of the major considerations was determined primarily by the degree to which they contribute to the qualifying condition; that is, the stronger the tie between the consideration and the qualifying condition, the greater the importance of the consideration. Each site was evaluated in terms of each major consideration, taking into account the contributing factors at that site.

The purpose of identifying major considerations for each guideline is to combine closely related site conditions so that the favorable and potentially adverse conditions can be considered on balance. A major consideration may be broader in scope than the combined scope of the related favorable and potentially adverse conditions, in order for it to relate more directly to the qualifying condition. Most guidelines that contain a disqualifying condition have one or more potentially adverse conditions that are related to the disqualifying condition. Since these potentially adverse conditions are considered in the formulation of a major consideration, the important aspects of the disqualifying conditions indirectly enter the comparative evaluation. Where a major consideration that is needed to evaluate the qualifying condition does not have a related favorable or potentially adverse condition, the consideration is derived directly from the qualifying or disqualifying condition. Not all contributing factors are discussed for each site; for brevity, only the factors that contribute to the evaluation of that consideration are discussed. The evaluation of each site with respect to each major consideration is presented in alphabetical order, by site.

The major considerations for the guidelines were then considered collectively, taking into account their relative importance, in a comparative evaluation of the sites. This comparative evaluation describes the sites with the most favorable combination of characteristics first and those with a less favorable combination of characteristics last.

The comparative evaluations of the sites are summarized in Sections 7.2 and 7.3 for the postclosure and the preclosure guidelines, respectively.

7.2 COMPARISON OF THE SITES ON THE BASIS OF THE POSTCLOSURE GUIDELINES

The postclosure guidelines are concerned with the characteristics, processes, and events that may affect the performance of the repository after closure. The objective is to ensure that the health and safety of the public will be protected for thousands of years, until the radioactivity of the waste has diminished to safe levels. This section presents a comparative evaluation of the five nominated sites against the postclosure guidelines.

7.2.1 TECHNICAL GUIDELINES

7.2.1.1 Geohydrology (postclosure)

The qualifying condition for geohydrology is as follows:

> The present and expected geohydrologic setting of a site shall be compatible with waste containment and isolation. The geohydrologic setting, considering the characteristics of and the processes operating within the geologic setting, shall permit compliance with (1) the requirements specified in 10 CFR 960.4-1 for radionuclide releases to the accessible environment and (2) the requirements specified in 10 CFR 60.113 for radionuclide releases from the engineered-barrier system using reasonably available technology.

Major considerations

On the basis of the favorable and potentially adverse conditions for this guideline, four major considerations (see Table 7-1) are identified that influence the favorability of the site with respect to the qualifying condition. These major considerations, in decreasing order of importance, are (1) ground-water travel time and flux, (2) changes in geohydrologic processes and conditions, (3) ease of characterization and modeling, and (4) presence of suitable ground-water sources. These major considerations are, in turn, influenced by a number of more specific geologic and hydrologic properties and in situ conditions called contributing factors.

Evaluation of the sites with respect to major considerations

Ground-water travel time and flux. This consideration covers the geohydrologic conditions that control the time of ground-water travel between the disturbed zone and the accessible environment and the ground-water flux (volumetric flow rate) across or through the repository and through the host rock to the accessible environment. It is related directly to the qualifying condition as a measure of the amount of ground water that can come in contact with the waste, the amount of ground water available to transport radionuclides between the repository and the accessible environment, the time delay for these radionuclides to reach the accessible environment, and the time available for radioactive decay during transport. This major consideration is derived from the first, fourth, and fifth favorable conditions of the geohydrology guideline. It is the most important of the major considerations because transport by ground water is the primary mechanism for radionuclide movement from the repository to the accessible environment.

The contributing factors for this consideration include the hydraulic conductivity and gradient, the effective porosity, the degree of saturation, the depth to the water table, the presence of flow through fractures or porous

Table 7-1. Guideline-condition findings by major consideration--geohydrology[a,b]

Condition	Davis Canyon	Deaf Smith	Hanford	Richton Dome	Yucca Mountain
MAJOR CONSIDERATION 1: GROUND-WATER TRAVEL TIME AND FLUX					
Favorable condition 1					
Site conditions such that the pre-waste-emplacement ground-water travel time along any path of likely radionuclide travel from the disturbed zone to the accessible environment would be more than 10,000 years.	P	P	P	P	P
Favorable condition 4					
For disposal in the saturated zone, at least one of the following pre-waste-emplacement conditions exists:	P	P	P	NP	NA
(i) A host rock and immediately surrounding geohydrologic units with low hydraulic conductivities.	P	P	NP	NP	NA
(ii) A downward or predominantly horizontal hydraulic gradient in the host rock and in the immediately surrounding geohydrologic units.	NP	P	NP	NP	NA
(iii) A low hydraulic gradient in and between the host rock and the immediately surrounding geohydrologic units.	NP	NP	P	NP	NA
(iv) High effective porosity together with low hydraulic conductivity in rock units along paths of likely radionuclide travel between the host rock and the accessible environment.	NP	NP	NP	NP	NA
Favorable condition 5					
For disposal in the unsaturated zone, at least one of the following pre-waste-emplacement conditions exists:	NA	NA	NA	NA	P
(i) A low and nearly constant degree of saturation in the host rock and in the immediately surrounding geohydrologic units.	NA	NA	NA	NA	NP
(ii) A water table sufficiently below the underground facility such that the fully saturated voids continuous with the water table do not encounter the host rock.	NA	NA	NA	NA	P
(iii) A geohydrologic unit above the host rock that would divert the downward infiltration of water beyond the limits of the emplaced waste.	NA	NA	NA	NA	NP
(iv) A host rock that provides for free drainage.	NA	NA	NA	NA	P
(v) A climatic regime in which the average annual historical precipitation is a small fraction of the average annual potential evapotranspiration.	NA	NA	NA	NA	P

Table 7-1. Guideline-condition findings by major consideration--geohydrology[a,b] (continued)

Condition	Davis Canyon	Deaf Smith	Hanford	Richton Dome	Yucca Mountain
MAJOR CONSIDERATION 2: CHANGES IN GEOHYDROLOGIC PROCESSES AND CONDITIONS					
Favorable condition 2					
The nature and rates of hydrologic processes operating within the geologic setting during the Quaternary Period would, if continued into the future, not affect or would favorably affect the ability of the geologic repository to isolate the waste during the next 100,000 years.	P	P	P	P	NP
Potentially adverse condition 1					
Expected changes in geohydrologic conditions--such as changes in the hydraulic gradient, the hydraulic conductivity, the effective porosity, and the ground-water flux through the host rock and the surrounding geohydrologic units--sufficient to significantly increase the transport of radionuclides to the accessible environment as compared with pre-waste-emplacement conditions.	NP	NP	NP	NP	NP
MAJOR CONSIDERATION 3: EASE OF CHARACTERIZING AND MODELING					
Favorable condition 3					
Sites that have stratigraphic, structural, and hydrologic features such that the geohydrologic system can be readily characterized and modeled with reasonable certainty.	NP	NP	NP	NP	NP
Potentially adverse condition 3					
The presence in the geologic setting of stratigraphic or structural features--such as dikes, sills, faults, shear zones, folds, dissolution effects, or bring pockets--if their presence could significantly contribute to the difficulty of characterizing or modeling the geohydrologic system.	P	P	P	P	P
MAJOR CONSIDERATION 4: PRESENCE OF SUITABLE GROUND-WATER SOURCES					
Potentially adverse condition 2					
The presence of ground-water sources, suitable for crop irrigation or human consumption without treatment, along ground-water-flow paths from the host rock to the accessible environment.	NP	NP	NP	NP	P

[a] Key: NA = not applicable; NP = for the purpose of this comparative evaluation, the favorable or potentially adverse condition is not present at the site; P = for the purpose of this comparative evaluation, the favorable or potentially adverse condition is present at the site.
[b] Analyses supporting the entries in this table are presented in Chapter 6 of the environmental assessment for each site.

media, net infiltration, the extent of the disturbed zone, and the distance to the accessible environment.

At each of the sites there are uncertainties in the conceptual model of ground-water flow, including the values of the key hydraulic parameters that control ground-water travel time and flux. Taking the uncertainties into account, there are ranges of possible travel times between the disturbed zone and the accessible environment at each site. Therefore, ground-water travel time was stochastically modeled at each site, using reasonably conservative geohydrologic assumptions and ranges of hydraulic parameters. Probabilistic ranges in travel time and the statistical probability for exceeding travel times of 1,000 and 10,000 years were derived for each site. In general, the ground-water flux is expected to be low to very low at each of the sites. A summary of the evaluation for each site follows.

At Davis Canyon, ground-water travel times from the disturbed zone to the accessible environment are modeled as porous-media flow vertically and horizontally through a layered sequence of differing lithologies (salts, anhydrite, dolomite, siltstone, etc.). The calculated travel times depend on the hydraulic conductivity and the effective porosities of the varying lithologies, the thickness and continuity of each layer, and the vertical and horizontal hydraulic gradients within and between each layer. Because the values of these parameters are uncertain, the expected ground-water pathways are uncertain. To quantify this uncertainty at Davis Canyon, a computer code was developed to evaluate the probability the distribution of travel times based on distribution of hydrologic parameters derived from data collected at a DOE test well (Gibson Dome No. 1) 5 kilometers (3 miles) north of the site, various oil test wells in the Paradox Basin, and various published sources of generic data. For purposes of analyzing the ground-water travel time, the outer edge of the disturbed zone was conservatively assumed to be at the top and bottom of the host salt bed, because of uncertainty in the extent of the disturbed zone. The time required for ground water to travel through the host salt bed is not included in the calculations of pre-waste-emplacement travel time to the accessible environment. The overall regional vertical hydraulic gradient between the upper and the lower hydrostratigraphic units, separated by the evaporite section containing the host salt bed, is generally downward. However, data collected at the Gibson Dome test well indicate both local downward and upward gradients between interbeds in the evaporite section containing the proposed host salt bed. The combined vertical and horizontal gradients in the area then result in either upward-to-lateral flow or downward-to-lateral flow within the layered sequence. Both the upward-to-lateral and downward-to-lateral travel times are analyzed, resulting in quite similar distributions.

The proposed controlled-area boundary for the Davis Canyon site is limited to a distance of 1 kilometer (0.6 mile) from the edge of the disturbed zone to the accessible environment due to the proximity of Canyonlands National Park in the expected direction of ground-water flow. For a lateral distance of 1 kilometer (0.6 mile) from the outer edge of the disturbed zone to the accessible environment, downward-to-lateral travel times were stochastically analyzed through 1,000 realizations of the model. This results in a probability of .003 for travel times of less than 1,000 years and probability of a .045 for less than 10,000 years. The median travel time is 240,000 years. A distance of 5 kilometers from the edge of the repository was also analyzed in case the boundary of the controlled area should change as a result of data developed during site characterization in a direction away from the Canyonlands National Park. This analysis results in a probability of less than 0.001 for travel times of less than 1,000 years and .006 for less than 10,000 years, with a median travel time of 880,000 years.

The Deaf Smith site is in a geohydrologic setting that is conceptually similar to that of the Davis Canyon site. A similar stochastic analysis of pre-waste-emplacement ground-water travel time was made. The computer flow model, as for Davis Canyon, consists of a series of layers representing a sequence of differing lithologies (salt, anhydrite, dolomite, siltstone, etc.), including the host salt bed. Only downward-to-lateral travel times were calculated, because only downward vertical hydraulic gradients have been observed in the vicinity of the site. The travel time was calculated beginning at the bottom of the salt repository bed (considered conservatively as the bottom edge of the disturbed zone) and extending 1 kilometer to the accessible environment. To consider the possibility that the boundary of the controlled area (and the distance to the accessible environment) might be extended, travel times were also calculated to the maximum 5-kilometer distance from the edge of the disturbed zone. The modeling is based on data obtained from literature reviews, analyses of water-well and petroleum-well records and pump testing, analyses of drill-stem tests, and analyses of laboratory tests conducted specifically for the repository program. There is a comparable level of uncertainty in the data bases for the Deaf Smith and the Davis Canyon sites. Considering porous-media flow as the likely flow mechanism, the results of travel-time analyses for an accessible environment 1 kilometer from the edge of the disturbed zone, on the basis of 1,000 realizations of the model, show a probability of .005 for travel times of less than 1,000 years and a probability of .107 for less than 10,000 years, with a median travel time of 87,000 years. For an accessible environment 5 kilometers from the edge of the disturbed zone, the probability of travel times of less than 1,000 years is less than .001, and the probability for less than 10,000 years is .015, with a median travel time of 500,000 years.

At the Hanford site, the stochastic analysis of the pre-waste-emplacement ground-water travel time used a conceptual model that is consistent with the current understanding of the deep ground-water flow system and considers the uncertainties in the hydraulic parameters used to predict travel times. In the analysis, ground-water flow is modeled along upward and lateral flow paths through an alternating sequence of basalt flows in which dense interiors of low permeability are separated by flow tops of higher permeability. The vertical and horizontal hydraulic-head gradients used in the stochastic model are deterministic; that is, they are based on quality head data obtained from piezometers at the site. The transmissivity values used in the model were based on site-specific test data that were varied over a reasonably conservative range. The range of effective porosity was estimated from geophysical logs, core samples, two tracer tests, and values reported in the literature. Key hydraulic parameters were conservatively evaluated over appreciable ranges in the model. The model considers ground-water movement that begins in the flow top immediately above the dense flow interior (the outer edge of the disturbed zone being within the dense interior host rock at an unknown distance from the flow top) of the proposed host rock and proceeds vertically upward and laterally to the accessible environment, 5 kilometers from the edge of the repository. The model conservatively does not include vertical travel time through the upper part of the undisturbed dense interior between the proposed repository and the base of the first flow top above the repository. The range of travel times derived from the model indicates a probability of .[illegible]3 or less for travel times of less than 1,000 years and a probability of .[illegible]2 or less for travel times of less than 10,000 years. This compares with the shortest median travel time for the conservative analyses of 22,000 years.

At the Richton site, the accessible environment is considered to be at the flank, or periphery, of the salt stock; therefore, ground-water travel times from the disturbed zone to the accessible environment (a minimum lateral distance of 244 meters (800 feet)) are judged to be within essentially pure salt. The mechanism for ground-water movement through the salt is uncertain. Because of the ductility of salt, which reduces the likelihood of open fractures, and the extremely low matrix hydraulic conductivity and porosity, there may be little or no water movement through the salt. However, to evaluate the travel time from the edge of the disturbed zone to the accessible environment, porous-media flow was conservatively assumed to prevail in the salt. Preliminary geologic studies have not identified anomalous features that would indicate the presence of preferential permeable flow paths in the salt stock. Fracture flow is considered unlikely and is not considered in the model. Flow is assumed to obey Darcy's law, and conservative ranges of the key hydraulic parameters are used; they are based on available generic in situ and laboratory data, including geophysical well logs. No site-specific data on hydraulic parameters are available. If alternative mechanisms of movement (e.g., diffusion) are considered, the estimated travel times to the accessible environment would be several million years.

The results of the stochastic modeling show a probability of less than .001 for travel times less than 1,000 or 10,000 years to the flank of the dome. Because of the very low hydraulic conductivities measured for essentially pure salt, the calculated times of lateral travel through 244 meters (800 feet) of salt are very long. Stochastic model calculations range over six orders of magnitude--the shortest being about 50,000 years and the median about 35 million years. Although the ranges of hydraulic parameters used in the analysis are considered reasonably conservative, a great deal of uncertainty is inherent in any prediction of travel times in millions of years. Of more significance than the absolute numbers, perhaps, is that the very long travel times suggested by the analysis indicate a likelihood that little or no ground water is present or moving through an appreciably thick, undisturbed mass of salt.

At Yucca Mountain, the stochastic analysis of the pre-waste-emplacement ground-water travel time from the disturbed zone to the accessible environment computes vertical ground-water movement downward through the unsaturated zone to the water table and then 5 kilometers laterally in the saturated tuff to the accessible environment. Travel time is calculated from a horizon 50 meters (164 feet) below the proposed repository downward through a minimum of about 135 meters (443 feet) of unsaturated welded and nonwelded tuff to the water table. Most of the total travel time is through the unsaturated zone, with about 140 years estimated for the travel time through the saturated zone to the accessible environment, once the water table is reached. Uncertainty in the variability and ranges in hydraulic conductivity and effective porosity are evaluated stochastically in the model, by randomly selecting ranges in hydraulic parameters in a series of 963 vertical columns. The calculated travel times range from about 9,500 to 80,250 years. This is based on an estimated maximum average net percolation of 0.5 millimeter per year. Ten realizations were run in each of the 963 columns of the model, with all but one of the 9,630 total realizations having a travel time of more than 10,000 years. The mean travel time in these calculations was about 43,300 years, and the median about 41,600, with a probability of about .0001 for a travel time of less than 10,000 years.

<u>Changes in geohydrologic processes and conditions</u>. This consideration covers the nature and rate of natural processes in the geologic setting that could ultimately change geohydrologic conditions so as to affect the ability of a repository to isolate the waste. It is directly related to the qualifying condition, which requires that geohydrologic conditions in the future be compatible with waste isolation. It is derived from the second favorable condition and the first potentially adverse condition. This consideration is second in importance because the preceding consideration, the ground-water travel time, reflects actual conditions, whereas this consideration reflects potential conditions.

Four contributing factors are identified for this consideration: climatic change, erosion, dissolution, and tectonics. On the basis of the discussion of these factors in Section 6.3.1 of each environmental assessment, it was concluded that climatic change is the only one of the four contributing factors that has a potential for significantly affecting the hydrologic system at any of the nominated sites during the next 100,000 years. Therefore, climatic change is the only potential cause of changes in the geohydrologic system that is addressed in the summary of site evaluations.

Judging from the record of the Quaternary Period in the area of the Davis Canyon site, climatic changes during pluvial conditions could increase precipitation, with a resulting increase in recharge to the ground-water system. Although it is uncertain to what extent higher rates of precipitation during the Quaternary Period have affected the hydrologic system, there is no evidence that ground-water parameters have changed significantly during the Quaternary Period. Also, the low permeability of the evaporite section separating the shallow hydrologic system from the deep confined system is expected to preclude any significant effects from expected climatic changes. Assuming that climatic changes during the next 100,000 years would be within the magnitude of past changes during the Quaternary Period, it does not appear that expected changes would adversely affect waste isolation at the Davis Canyon site during the next 100,000 years.

Judging from the record of the Quaternary Period, precipitation may be expected to increase over the current levels for the area of the Deaf Smith site, with consequent increases in recharge during the next 100,000 years. However, because of the low permeability of the evaporite section and the fine sedimentary interbeds that separate the shallow hydrologic system from the deep confined system beneath the proposed repository horizon, the variations in the nature and rates of surficial hydrologic processes that would result from future climatic changes would have little effect on the ability of a repository at the site to isolate waste during the next 100,000 years.

The climatic history of the Quaternary Period at the Hanford site indicates that any hydrologic impacts due to climatic changes would be localized or shallow phenomena (e.g., glacially induced flooding) that would not significantly change the waste-isolation potential of the deep basalt environment during the next 100,000 years. The factors responsible for this include the low permeability of the basalt flow interiors between the land surface and the proposed repository depth; the relatively low permeability of the deep basalt flows in comparison with shallow flows and interbeds; the existence of different flow systems with depth; the short duration of floods; and the likely persistence of the arid to semiarid climate that has existed at Hanford over the past 3 million years.

For the Richton site, the Quaternary history of the region indicates that climatic changes would have no significant influence on geohydrologic conditions at the site. Variations in geohydrologic processes that have occurred in response to Quaternary climatic cycles and the associated sea-level fluctuations result in slight increases and decreases in precipitation, hydraulic gradients, and rates of ground-water movement in the geohydrologic system surrounding the salt dome. Because of the very low hydraulic conductivity of the dome salt, such slight variations in hydrologic processes are expected to have minor, if any, effects on fluid movement within the dome. Therefore, no natural geohydrologic changes that would affect waste during the next 100,000 years are expected at the site.

At Yucca Mountain, the climatic record of the Quaternary Period suggests that pluvial conditions may recur sometime during the next 100,000 years, resulting in increased net infiltration (flux) and recharge, which could in turn raise the level of the water table toward the repository. Such changes would tend to reduce the time of ground-water travel between the disturbed zone and the accessible environment and could result in some increase in the quantity of ground water coming in to contact with the waste.

Ease of characterization and modeling. This consideration addresses the complexity of the geohydrologic system in terms of whether it can be characterized and modeled with reasonable certainty. It relates to the qualifying condition because characterization is the process of collecting and analyzing the data needed to develop and perform the modeling that is the means for predicting whether the site is compatible with waste containment and isolation. This major consideration is derived from the third favorable condition and the third potentially adverse condition. Since it is not an intrinsic physical characteristic of the geohydrologic setting, this consideration is not as important as the first two considerations; however, the ability to characterize and model the geohydrologic system with reasonable certainty is essential to evaluating the geohydrologic processes and properties that affect the ability of the site to contain and isolate waste.

Some of the contributing factors that influence the ease of characterization and modeling are the presence of faults, folds, brine pockets, dissolution effects, lithologic variations, interrelationships among hydrostratigraphic units, availability of testing techniques and analytic models, and understanding of flow mechanisms.

All five nominated sites are, to varying degrees, presently judged to have geologic and hydrologic complexities that could preclude their being readily characterized or modeled with reasonable certainty. Appreciable differences exist from one site to another in present levels of uncertainty, in part because of imbalances in the quality and quantity of available data and stages of scientific and technical investigation. A good understanding of the geohydrology of the site must be developed through the characterization process before it can be modeled with reasonable certainty. Modeling, in turn, can determine which physical characteristics need to be characterized. The difficulty of characterizing a site limits the ability to model it to an acceptable level of certainty. Although the third favorable condition is not present and the third potentially adverse condition is present at each site, it is expected that all five sites can be adequately characterized, though with varying levels of difficulty, in order to model their capabilities for long-term waste isolation to acceptable levels of certainty. A summary of the evaluation for this consideration for each site follows.

At the Davis Canyon site, the regional geologic framework and limited site-specific data suggest that the site is stratigraphically and structurally uncomplicated. Present stratigraphic information indicates that the proposed host salt bed contains minimal impurities and is a part of a reasonably well-understood sedimentary sequence. However, the present limited investigations leave many uncertainties. Structural features like faults, folds, and dissolution zones within the geologic setting could contribute to the difficulty of characterizing the system if they are found within the site. Ground-water movement through deep salt beds may be practically nil. There is a need to develop a clear understanding of the movement of fluids in salt and a site-specific ground-water hydraulics data base and to evaluate the potential for significant fracture flow in hydrogeologic units surrounding the host rock.

Because they are in similar geohydrologic settings, the Deaf Smith site and the Davis Canyon site are similar with respect to the ease of characterizing and modeling. Somewhat more data are presently available for the Deaf Smith site than for Davis Canyon, but fewer site-specific data are available for the salt sites than for the nonsalt sites. The greater number and frequency of nonsalt interbeds at Deaf Smith introduces complicating factors that are less likely to be present at Davis Canyon. As at Davis Canyon, the potential for significant fracture flow in geohydrologic units surrounding the host rock at Deaf Smith needs to be evaluated.

Generically, the horizontal distribution, variations in thickness and internal variations in the thickness of multiple basalt flows like those at Hanford may be more difficult to predict with confidence than for a sequence of sedimentary rocks like those formed at the bedded-salt sites, but site-specific investigations are more advanced at the Hanford site than at any of the salt sites. Consequently, the data base is appreciably larger and the complexities of site characterization and modeling are better defined at Hanford. Geologic features like faults, folds, internal variations in the thickness of flows, and variations in original intraflow structures known to exist in the regional setting could contribute to difficulty in modeling. Although uncertainties remain, preliminary studies have defined some basic geologic and hydrologic characteristics of the site. The existence of multiple basalt flows can complicate the characterization and modeling of the flow system, as well as provide multiple barriers to fluid movement. Accepted concepts and methods for studying saturated flow in a layered geohydrologic system are applicable to the basalt-flow system beneath Hanford. In some ways this may make characterization and modeling less complicated than at sites where applicable fluid-flow theory is either more complex or less advanced, such as for flow in salt or in the unsaturated zone at Yucca Mountain.

At the Richton site, the boundaries and dimensions of the salt stock are easonably well defined. Limited available data on the interior haracteristics of the salt stock suggest that it consists largely of pure alt that is free of significant anomalous features (e.g., large faults or lastic inclusions) that would provide important preferential ground-water low paths. However, this concept of the dome's interior is uncertain and equires additional data for confirmation. Also, data on the surrounding eohydrologic environment mainly provide a regional picture of the round-water flow system outside the dome, with little site-specific nformation to define flow relationships near the interface of the salt stock nd the adjacent hydrostratigraphic units. These relationships may be complex nd difficult to characterize, requiring an extensive data base that would be ifficult to acquire. The characteristics of ground-water movement, if any, ithin salt are not well understood. Therefore, there is uncertainty in how o characterize and model fluid movement within the dome and any exchange of round water between the dome and the surrounding geohydrologic units. On the ther hand, because the accessible environment at the Richton Dome begins at he edge of the salt stock, the controlled area extends only to the periphery f the dome. The most critical part of the geohydrologic system to be haracterized and modeled is confined to what may be an essentially omogeneous medium, the interior salt mass of the dome. In this respect, the low system may be regarded as less complex and difficult to characterize and odel than a system that contains a variety of lithologies or flow media etween the repository and the accessible environment. However, the mechanism or ground-water flow in the salt, if such flow is significant, needs to be learly defined during site characterization.

The geologic setting at Yucca Mountain may be considered somewhat omplex, considering the structural history and volcanic origin of Yucca Mountain, and the inherent uncertainties in predicting the lateral and ertical variability of volcanic rock units. Also, the site is relatively omplex from the standpoint of the availability of state-of-the-art models for easuring and analyzing flow in the unsaturated zone rather than the saturated one. Known local faulting adds to the complexity of site characterization nd modeling. However, the progress of site-specific geologic and hydrologic nvestigations is comparable to that at the Hanford site and more advanced han those performed at any of the salt sites. A preliminary site-specific eohydrologic data base has been established, and preliminary details of a onceptual flow model of the unsaturated zone, are defined. Advanced echniques are being developed to measure and analyze hydrologic parameters nd to provide the information needed to refine models of flow in the nsaturated zone. Because of the need to develop advanced techniques and ethods, the difficulty of characterizing and modeling the site with easonable certainty may be greater than at sites in the saturated zone where urrently accepted methods may be adequate for characterizing and modeling.

<u>Presence of suitable ground-water sources</u>. This consideration addresses he potential for radionuclides migrating from a repository to mix with round-water sources suitable for crop irrigation or human consumption without reatment along flow paths to the accessible environment. It pertains to the ualifying condition with respect to limitations on radionuclide releases to he accessible environment and is derived from the second potentially adverse ondition. This consideration is less important than the other three, because

it is unlikely that ground-water resources could be contaminated if a site is selected on the basis of its ability to isolate wastes, as reflected in the other three considerations. Of the five nominated sites, only Yucca Mountain has a finding of present for the second potentially adverse condition. A summary of the evaluation for each site follows.

At Davis Canyon a low-yielding aquifer containing good-quality ground water is present at a relatively shallow depth above the proposed repository horizon. However, ground water of good quality usable for irrigation or human consumption without treatment is not present along probable ground-water flow paths between the disturbed zone and the accessible environment. Although there is some potential for locally upward flow from the host rock, flow paths would be diverted laterally or downward at least hundreds of meters below the shallow aquifer because of the regionally downward vertical gradient below the shallow aquifer.

At the Deaf Smith site, ground-water flow is expected to be downward from the repository horizon. Water along this flow path has high total-dissolved-solids concentrations, making it unusable for crop irrigation or human consumption without treatment. There is good-quality ground water at shallow depths above the proposed repository horizon, but upward flow is not expected from the host rock.

At the Hanford site, shallow aquifers containing water of good quality exist above likely flow paths from the preferred repository horizon. However, ground water along likely flow paths between the disturbed zone and the accessible environment contains flouride, boron, and sodium concentrations considered too high for crop irrigation or human consumption without treatment.

At the Richton site, the accessible environment is considered to be at the flank of the salt stock. Therefore, ground water suitable for crop irrigation or human consumption without treatment does not occur along ground-water flow paths between the disturbed zone and the accessible environment.

At Yucca Mountain, flow paths from the disturbed zone in the unsaturated zone would be expected to be vertically downward to the water table and then laterally through the saturated zone to the accessible environment. Ground water along the flow paths in the saturated zone is of good quality and suitable for crop irrigation and human consumption without treatment.

Summary of the comparative evaluation

The Richton Dome is the most favorable of the five nominated sites for the geohydrology guideline on the basis of the four major considerations addressed under this guideline. Although site-specific data are sparse, resulting in appreciable uncertainty about flow in geohydrologic units surrounding the dome, and the mechanism of fluid flow in salt is uncertain, ground-water travel times at Richton are expected to be very long, and very little, if any, ground-water movement takes place within the salt stock. It is likely that no ground water or only very little is contained in the salt stock. Uncertainty with respect to the possible presence of anomalous features that could significantly affect flow through the dome would be addressed during site characterization. Hydrologic processes and conditions are not expected to change in a manner that would unfavorably affect the ability of the repository to isolate waste. Modeling of the geohydrologic system surrounding the dome is expected to be difficult. The limited data base results in appreciable uncertainty about relationships between the dome and the surrounding system. However, because all pathways to the accessible environment are expected to be entirely within the salt host rock, there is a high level of certainty that no usable ground-water sources would be encountered along pathways to the accessible environment.

Davis Canyon is the next most favorable site with respect to the geohydrology guideline if it is compared to Deaf Smith on the basis of equal distances to the accessible environment. It is slightly less favorable than the Richton Dome on the first and most important major consideration and is equally favorable with the other sites on the second major consideration. The pre-waste-emplacement travel time from the disturbed zone to the accessible environment appears to be less than that at the Richton Dome, and the travel time at Davis Canyon is longer than at the Deaf Smith site for equal distances to the accessible environment at both sites. The ground-water flux through the salt host rock, as indicated by the generic understanding of the hydraulic properties of salt, may be small if not nonexistent. There is no evidence for natural geohydrologic changes that will unfavorably affect the ability of the repository to isolate the waste during the next 100,000 years. On the basis of regional geologic studies, the structure and stratigraphy of the site are considered uncomplicated, but because of uncertainties with respect to the mechanism for ground-water flow in salt and the unlikely potential occurrence of a really extensive, fracture-controlled pathways in the brittle sedimentary interbeds, the level of difficulty in characterizing and modeling the geohydrologic system with reasonable certainty is expected to be comparable with that of the other sites. No aquifers containing ground water that is usable without treatment are present along any likely ground-water pathways between the edge of the disturbed zone and the accessible environment.

The Deaf Smith site is less favorable than the Richton and the Davis Canyon sites for the geohydrology guideline when the accessible environment is equally distant from the disturbed zone at Deaf Smith and at Davis Canyon. In such a case, it is less favorable on the first and most important major consideration, but equally favorable on the second major consideration. The estimated pre-waste-emplacement ground-water travel time between the disturbed zone and the accessible environment is shorter than that at Davis Canyon and Richton. However, if the distance to the accessible environment at Deaf Smith should be lengthened up to 5 kilometers and at Davis Canyon remain at 1 kilometer, Deaf Smith would be the more favorable site with respect to the pre-waste-emplacement ground-water travel time. Although the ground-water flux within the salt host rock is expected to be low, the presence of fine clastic interbeds in the host rock results in a potential for higher flux at Deaf Smith than at Davis Canyon or Richton. No natural changes in geohydrologic conditions that would unfavorably affect the ability of the site to isolate waste during the next 100,000 years are indicated. The structure and stratigraphy of the Deaf Smith site, on the basis of regional geologic studies, are considered uncomplicated. Because of uncertainties with respect to the mechanism for ground-water flow in salt and the unlikely potential for areally extensive, fracture-controlled pathways in the brittle interbeds, the level of difficulty in characterizing and modeling the geohydrologic system is expected to be comparable with that of the other sites. Finally, there is a high level of certainty that no aquifers containing ground water usable without treatment are present along ground-water pathways between the edge of the disturbed zone and the accessible environment.

The Hanford and the Yucca Mountain sites are both less favorable than the salt sites, but are in a comparable range of favorability with each other. Their comparative evaluations vary from one major consideration to another on the basis of available information. With respect to the pre-waste-emplacement ground-water travel time, Yucca Mountain is more favorable than the Hanford site. At Yucca Mountain, the ground-water flux through the host rock and the surrounding geohydrologic units, as indicated by the estimated maximum annual infiltration of 0.5 millimeter, is expected to be very low. A return to pluvial climatic conditions could increase the flux rate through the host rock and the surrounding geohydrologic units. This could also cause some rise in the water table toward the repository and some reduction in the time of travel to the accessible environment. Yucca Mountain and Hanford appear to have similar ranges of structural and stratigraphic complexity with unique geohydrologic complexities at each site. The complexity of fracture systems at Yucca Mountain may have important implications for characterizing and modeling flow in the unsaturated zone with reasonable certainty. Uncertainty in how to model flow in the unsaturated zone may also add to the difficulty of characterizing and modeling at Yucca Mountain. Ground-water sources of good quality are located along likely ground-water pathways from the proposed repository to the accessible environment at Yucca Mountain.

At the Hanford site, the ground-water flux through the saturated host rock and the surrounding geohydrologic units may be higher than in the unsaturated zone at Yucca Mountain. For the second major consideration, Hanford is more favorable than Yucca Mountain. Expected natural changes in hydrologic processes or geohydrologic conditions are not expected to affect the ability of a repository to isolate the waste during the next 100,000 years. Although commonly used modeling techniques may be applied, uncertainties in the structural and stratigraphic heterogeneity of the multiple basalt flows may contribute to modeling difficulties. At Hanford, no sources of ground water suitable for crop irrigation or human consumption without treatment are present along likely ground-water pathways from the edge of the disturbed zone to the accessible environment.

7.2.1.2 Geochemistry

The qualifying condition for postclosure geochemistry is as follows:

> The present and expected geochemical characteristics of a site shall be compatible with waste containment and isolation. Considering the likely chemical interactions among radionuclides, the host rock, and the ground water, the characteristics of and the processes operating within the geologic setting shall permit compliance with (1) the requirements specified in §960.4-1 for radionuclide releases to the accessible environment and (2) the requirements specified in 10 CFR 60.113 for radionuclide releases from the engineered-barrier system using reasonably available technology.

Major considerations

On the basis of the qualifying, favorable, and potentially adverse conditions for this guideline (see Table 7-2), three major considerations are identified that influence the favorability of the site with respect to the qualifying condition are identified. In order of decreasing importance, they are (1) the expected rate of mass transfer of radionuclides from the waste package, (2) geochemical conditions that would inhibit the transport of radionuclides into the accessible environment, and (3) geochemical effects on the sorptive properties and strength of the host rock.

Evaluation of the sites in terms of the major considerations

Mass transfer of radionuclides. This consideration includes geochemical conditions in the immediate vicinity of the waste package after the permanent closure of the repository. It relates directly to the qualifying condition through the rates of radionuclide dissolution from the waste form and is based on the second and fourth favorable conditions and the first potentially adverse condition. The mass transfer of radionuclides is the most important consideration because it describes the processes by which radionuclides that are initially sealed in the solid waste form as part of the waste package will be released to the ground-water system (e.g., as ions, complexes, or particulates) or be contained within the engineered-barrier system. The most important contributing factors are the volumetric flow rate of the ground water that may contact the waste package and the chemistry of the ground water. Other contributing factors include the potential for the precipitation and sorption of radionuclides; the potential for the formation of colloids, complexes, and particulates; oxidation-reduction conditions; and the chemical reactivity of the ground water. A summary of the evaluation for each site follows.

The bedded salt of the Davis Canyon site contains little ground water. Sources of water in the repository horizon include brine inclusions and water of carnallite hydration, which constitute a small fraction of the host-rock volume. Thus, the volumetric flow rate of ground water due to the migration of these waters at the repository horizon is expected to be extremely low, if present at all. Because of their high magnesium content, the brines at Davis Canyon are potentially very corrosive for the stainless-steel container of the waste package. However, waste-package degradation should be limited because the amount of water in contact with the waste is expected to be small. The formation of some colloids will be inhibited by the high salinity of brine. Because of their high concentration in the brines, chlorides, sulfates, and carbonates could form complexes with radionuclides, which may increase the mobility of some radionuclides. Although chemically reducing conditions are expected in the host rock and the underlying aquifers, the ability of the water-rock system to maintain reducing conditions in the presence of alpha and gamma radiolysis may be limited.

The host rock at the Deaf Smith site is bedded salt that may contain more water than the rock of the other two salt sites. The salt of the lower San Andres Unit 4 contains intercrystalline muds and interbeds of mudstone containing clay; these muds and interbeds could contribute water in addition to that provided by brine inclusions. Thus, the total amount of ground water that is expected to enter the repository through brine migration should be extremely small. These brines have a high magnesium content and are

Table 7-2 Guideline-condition findings by major consideration--geochemistry[a,b]

Condition	Davis Canyon	Deaf Smith	Hanford	Richton Dome	Yucca Mountain
MAJOR CONSIDERATION 1: EXPECTED RATE OF MASS TRANSFER FROM THE WASTE-PACKAGE SUBSYSTEM					
Favorable condition 2					
Geochemical conditions that promote the precipitation, diffusion into the rock matrix, or sorption of radionuclides; inhibit the formation of particulates, colloids, inorganic complexes, or organic complexes that increase the mobility of radionuclides; or inhibit the transport of radionuclides by particulates, colloids, or complexes.	P	P	P	P	P
Favorable condition 4					
A combination of expected geochemical conditions and a volumetric flow rate of water in the host rock that would allow less than 0.001 percent per year of the total radionuclide inventory in the repository at 1,000 years to be dissolved.	P	P	P	P	P
Potentially adverse conditions 1					
Ground-water conditions in the host rock that could affect the solubility or the chemical reactivity of the engineered-barrier system to the extent that the expected repository performance could be compromised.	NP	NP	NP	NP	NP
MAJOR CONSIDERATION 2: GEOCHEMICAL CONDITIONS THAT WOULD INHIBIT RADIONUCLIDE TRANSPORT IN THE FAR FIELD					
Favorable condition 1					
The nature of rates of the geochemical processes operating within the geologic setting during the Quaternary Period would, if continued into the future, not affect or would favorably affect the ability of the geologic repository to isolate the waste during the next 100,000 years.	P	P	P	P	P
Favorable condition 2					
Geochemical conditions that promote the precipitation, diffusion into the rock matrix, or sorption of radionuclides; inhibit the formation of particulates, colloids, inorganic complexes, or organic complexes that increase the mobility of radionuclides; or inhibit the transport of radionuclides by particulates, colloids, or complexes.	P	P	P	P	P

8 0 0 0 8 0 9 6 8

Table 7-2. Guideline-condition findings by major consideration--geochemistry[a,b] (continued)

Condition	Davis Canyon	Deaf Smith	Hanford	Richton Dome	Yucca Mountain
MAJOR CONSIDERATION 2: GEOCHEMICAL CONDITIONS THAT WOULD INHIBIT RADIONUCLIDE TRANSPORT IN THE FAR FIELD (Continued)					
Favorable condition 5					
Any combination of geochemical and physical retardation processes that would decrease the predicted peak cumulative releases of radionuclides to the accessible environment by a factor of 10 as compared to those predicted on the basis of ground-water travel time without such retardation.	NP	N.	P	NP	P
Potentially adverse condition 3					
Pre-waste-emplacement ground-water conditions in the host rock that are chemically oxidizing.	NP	NP	NP	NP	P
MAJOR CONSIDERATION 3: GEOCHEMICAL EFFECTS ON THE SORPTIVE PROPERTIES AND ROCK STRENGTH OF HOST ROCK					
Favorable condition 3					
Mineral assemblages that, when subjected to expected repository conditions, would remain unaltered or would alter to mineral assemblages with equal or increased capability to retard radionuclide transport.	P	P	P	P	P
Potentially adverse condition 2					
Geochemical processes or conditions that could reduce the sorption of radionuclides or degrade the rock strength.	NP	NP	NP	NP	NP

[a] Key: NP = for the purpose of this comparative evaluation, the favorable or potentially adverse condition is not present at the site; P = for the purpose of this comparative evaluation, the condition is present at the site.

[b] Analyses supporting the entries in this table are presented in Chapter 6 of the environmental assessment for each site.

potentially very corrosive to the stainless-steel container of the waste packages, but the small amount of water expected in the repository will limit waste-package degradation. The formation of some, but not all, colloids will be inhibited by the high salinity of brine. Because of their high concentrations in the brine, chlorides, sulfates, and carbonates could form complexes with radionuclides, which may increase the mobility of some radionuclides. While chemically reducing conditions are expected in the host rock and underlying aquifers, the ability of the water-rock system to maintain reducing conditions in the presence of alpha and gamma radiolysis may be limited.

The Hanford site may have a somewhat higher flow rate of water past the waste package than other sites. The bentonite and crushed-basalt packing material that will surround the low-carbon-steel disposal containers is expected to significantly reduce the flow rate of ground water that could come in contact with the waste. The ground water at Hanford has a low salinity in comparison with the salt sites and a high pH, which tends to reduce the rates of container corrosion. In addition, the chemically reducing conditions that are expected would lower the solubility of redox-sensitive radionuclides and further lower the rates of container corrosion. However, alpha and gamma radiolysis may result in localized oxidizing conditions around the disposal container. Ground water at the repository level contains carbonate and hydroxyl ions, which could complex with escaping radionuclides, thereby increasing their mobility. Interactions between the waste package and ground water may result in the precipitation of iron-silica that would tend to scavenge radionuclides. In addition, sorption is expected to play a major role in the retardation of radionuclide transport.

Richton Dome is probably driest of the salt sites because of the small quantity of brine inclusions typical of domed salt. The volumetric flow rate of ground water at the repository horizon from brine migration is expected to be extremely low. As a result, waste-package degradation should be limited in spite of the inherently corrosive nature of brine. The formation of some, but not all, colloids should be inhibited by the high salinity of brine. The chloride and sulfate present in the brine could form complex with, and thus increase the mobility of, some radionuclides. While chemically reducing conditions are expected in the host rock, the ability of the water-rock system to maintain reducing conditions in the presence of alpha and gamma radiolysis may be limited.

The Yucca Mountain site is in a geologic environment with a very low ground-water flux through the candidate repository horizon. The low salinity and the nearly-neutral pH of the ground water would tend to reduce the corrosion rate of the disposal container; however, the ground water is oxidizing and would tend to make the waste-package environment somewhat more corrosive than water with lower oxidation-reduction (redox) conditions. The potential for the formation of inorganic complexes in the ground water of the Yucca Mountain site is probably low because of the very low salinity of the water, although the carbonate present in the ground water may increase the mobility of some radionuclides. The nearly-neutral pH of the water is conducive to the low solubility of oxides and hydroxides of some radionuclides, especially the actinides. In addition, interactions between the waste package and ground water may result in the precipitation of iron-silica, which would tend to scavenge radionuclides.

Radionuclide transport. This major consideration relates directly to the qualifying condition with respect to the natural barriers that would inhibit the transport of radionuclides into the accessible environment; it is based on the first, second, and fifth favorable conditions and the third potentially adverse condition. The contributing factors that are the most important for the quantitative evaluation of radionuclide transport and retardation include sorption and precipitation as well as redox conditions. A summary of the evaluation for each site follows.

At the Davis Canyon site, the geochemical processes within the host rock are not expected to be altered by anything other than the dissolution of the host salt, and available data suggest that dissolution will not be a problem at Davis Canyon. The salt contains very small amounts of clay minerals that could enhance the sorption of migrating radionuclides Conversely, the high ionic strength of the brine would tend to decrease the sorptive capacity of these clays. Redox conditions in the interbeds within the salt cycles and in the aquifer beneath the salt of the Paradox Formation are reducing, which decreases the solubility of some key redox-sensitive radionuclides. However, the chloride and carbonate, which are present in the brines in high concentration, could form complexes with radionuclides, and this may increase the mobility of these radionuclides. However, sulfate solubility relationships may limit the concentrations of some radionuclides.

At the Deaf Smith site, geochemical processes would not be expected to be altered by anything other than the dissolution of the host salt, and dissolution is not expected to be a problem at the site. The salt of the Deaf Smith site contains numerous mudstone inclusions and interbeds, and approximately half of them are composed of clay and clay-sized particles. Although it is possible that the clay could increase the sorption of migrating radionuclides, the high ionic strength of the brine tends to decrease the sorptive capacity of the clay. Ground water in the aquifer that underlies the salt cycles of the Palo Duro Basin is reducing, which further decreases the solubility of some key redox-sensitive radionuclides. However, the chloride and carbonate present in the brine could form complexes with radionuclides, thereby increasing their mobility. However, sulfate solubility relationships may limit the concentrations of some radionuclides.

At the Hanford site, little change is expected in the geochemical processes within the basalts because of the depth and the saturation of the repository horizon. The dense interior of the host rock should afford some degree of physical retardation for radionuclides. The geochemical environment of the site is favorable for the precipitation and sorption of radionuclides (i.e., reducing ground water and abundant secondary clays and zeolites from lining fracture and fragment surfaces). The secondary mineral assemblages that would be formed are believed to be stable under the temperatures expected in the disturbed zone. Since the data on colloids, particulates, and organics are limited, these factors cannot be fully evaluated at present. The ground water is of low salinity, but it contains carbonate and hydroxyl ions that could form complexes with radionuclides.

At the Richton site, the geochemical processes within the host rock would not be expected to be altered by anything other than dissolution. Available data suggest that dissolution should not be a problem at the site. The salt of the Richton Dome is predominantly halite with a very low water content.

Available data suggest that the water contained in fluid inclusions in the salt is reducing and should decrease the solubility of some redox-sensitive radionuclides. Because of their high concentrations, the chloride, sulfate, and carbonate present in the brines could form complexes with radionuclides, thereby increasing their mobility. However, sulfate solubility relationships may limit the concentration of some radionuclides.

At Yucca Mountain, little water is expected to pass through the tuff. The predominant mode of water migration is currently thought to be matrix flow along much of the ground-water-flow path. Sorption and diffusion are expected to delay or retard the migration of radionuclides. The oxidizing nature of the water may inhibit radionuclide precipitation and sorption for redox-sensitive radionuclides. The abundance of highly sorptive secondary clays and zeolites along ground-water-flow paths should provide a sorptive barrier to most radionuclides. Redox-sensitive radionuclides like technetium may not be retarded by sorption. The low salinity of the ground water would be conducive to the formation of some colloids since certain actinides form colloids in dilute nearly-neutral waters. Since the data on colloids, particulates, and organics are limited, these factors, cannot be fully evaluated at present.

Sorption and rock strength. This consideration addresses geochemical processes that could adversely affect the sorptive capacity or strength of the host rock, or both. The consideration relates directly to the qualifying condition with respect to the retardation of radionuclides by natural barriers in the repository and along ground-water-flow paths to the accessible environment; it is derived from the third favorable condition and the second potentially adverse condition. Sorption and rock strength are considered less important that the preceding considerations because they would affect only a small percentage of the total rock mass surrounding the repository. Change in the sorptive capacity of the host rock minerals is the most important contributing factor under this consideration because of the potential effect on the retardation of radionuclides. The major contributing factors for this consideration are the stability of mineral assemblages, the effects of mineral alteration on sorption, and the effects of mineral alteration on rock strength. A summary of the evaluation for each site follows.

The mineral assemblage at the Davis Canyon site may contain carnallite, which could dehydrate when subjected to repository heat and release magnesium-rich brines. High-magnesium brines would accelerate the degradation of the waste packages and subsequently lead to a release of radionuclides. In addition, alteration of the carnallite could reduce the strength of the host rock. However, the quantity of carnallite at the Davis Canyon site is expected to be small, and carnallite should have little effect on radionuclide containment.

The mineral assemblage at the Deaf Smith site includes interbeds and inclusions of mudstone. It is assumed that these consist of approximately 50 percent clay minerals that may dehydrate under the geochemical conditions within the repository. However, because of the small volume of clay minerals, the alteration of these materials is not expected to affect the retardation of radionuclides or the strength of the host rock.

The host rock at the Hanford site consists of basalt and a number of sorptive secondary minerals (e.g., clays, zeolites). Laboratory tests suggest that repository conditions may result in the formation of a mineral assemblage similar to the secondary minerals formed naturally in basalt as a result of hydrothermal alteration. Although the hydrothermal conditions near the repository could adversely affect the sorptive capacity of some of these minerals, there is abundant evidence that hydrothermal conditions could alter the volcanic materials to more sorptive materials (e. ., clays and zeolites). In general, the effects of the repository on rock strength are expected to be negligible.

At the Richton site, the mineral assemblage consists mainly of halite with some anhydrite. Because of the stability of the minerals at this site, it is expected that no geochemical alteration or reduction in rock strength would affect the transport of radionuclides.

The mineral assemblage in the host rock of the Yucca Mountain site consists of 98 percent quartz, feldspar, and cristobalite, with small amounts of secondary clays and zeolites. The sorptive capacity of the host rock is likely to be slightly reduced by the dehydration of clays and zeolites in the disturbed zone and remain unaffected in the surrounding rocks. Only very small amounts of volcanic glass are likely to be present. Rock strength is not expected to be affected by the geochemical conditions in the repository.

Summary of comparative evaluations

Hanford and Yucca Mountain are the most favorable sites for the geochemistry guideline. These two sites are expected to have the most favorable geochemical conditions with respect to the waste package and radionuclide retardation. The basalt at Hanford should respond favorably to geochemical conditions in the repository by creating additional sorptive capacity. Hanford also has more favorable redox conditions. Yucca Mountain has unsaturated conditions as well as the additional radionuclide-retardation effects of matrix diffusion.

The Davis Canyon, the Deaf Smith, and the Richton sites are favorable for all major considerations and are essentially equivalent with respect to the geochemistry guideline. They are less favorable than the nonsalt sites because the sorptive capacity of salt is very limited and the brines at these three sites could reduce the lifetime of the waste package. Moreover, the geochemical conditions in the salt sites are not expected to enhance the retardation of radionuclides through the alteration of the host rock to the degree that is expected at Hanford. The amount of brine, however, will probably be small, and the transport of radionuclides by this brine is likely to be quite limited. Therefore retardation due to geochemical effects may be of limited importance.

7.2.1.3 Rock characteristics (postclosure)

The qualifying condition for postclosure rock characteristics is as follows:

> The present and expected characteristics of the host rock and surrounding units shall be capable of accommodating the thermal, chemical, mechanical, and radiation stresses expected to be induced by repository construction, operation, and closure and by expected interactions among the waste, host rock, ground water, and engineered components. The characteristics of and the processes operating within the geologic setting shall permit compliance with (1) the requirements specified in §960.4-1 for radionuclide releases to the accessible environment and (2) the requirements set forth in 10 CFR 60.113 for radionuclide releases from the engineered-barrier system using reasonably available technology.

Major considerations

On the basis of the qualifying, favorable, and potentially adverse conditions for this guideline (see Table 7-3), three major considerations are identified that influence the favorability of the sites with respect to the qualifying condition. In order of decreasing importance, they are (1) the potential effects of repository-induced heat on waste containment or isolation, (2) the complexity of engineering measures required to ensure waste containment and isolation, and (3) flexibility for locating the underground facility to ensure waste isolation. These major considerations are, in turn, influenced by a number of more-specific rock properties and in situ conditions.

Evaluation of the sites in terms of the major considerations

Effects of repository-induced heat. This consideration is derived from the second favorable condition and second and third potentially adverse conditions. The factors contributing to this condition are the thermal properties of the host rock, such as thermal conductivity and the coefficient of thermal expansion; mechanical properties, such as a sufficiently high ductility for fractures to heal; thermomechanical behavior, such as the potential for thermally induced fractures; and geochemical conditions, such as the potential for brine migration and the hydration or dehydration of mineral components. This consideration also takes into account the effect of repository-induced heat on the integrity of the host rock and the surrounding rock units. Because of the potential effects of these factors on waste isolation, this major consideration is more important than the other two. A summary of the evaluation for each site follows.

At Davis Canyon, the effect of repository-induced temperature increases after closure can be favorable because of increases in the rate of salt creep, which would seal the underground openings and reconsolidate and recrystallize the salt backfill. Adverse impacts from a temperature increase would include the migration of brine within the host rock to the heat source and an increase in gas pressure if brines or gases are present in significant quantities. Limited site-specific data indicate very little brine is present at Davis Canyon. The adverse geochemical impacts from a temperature increase could also include mineral alteration and the dehydration of carnallite, but test

Table 7-3. Guideline-condition findings by major consideration--rock characteristics (postclosure)[a,b]

Condition	Davis Canyon	Deaf Smith	Hanford	Richton Dome	Yucca Mountain
MAJOR CONSIDERATION 1: POTENTIAL IMPACT OF REPOSITORY-INDUCED HEAT ON WASTE CONTAINMENT OR ISOLATION					
Favorable condition 2					
A host rock with a high thermal conductivity, a low coefficient of thermal expansion, or sufficient ductility to seal fractures induced by repository construction, operation, or closure or by interactions among the waste, host rock, ground water, and engineered components.	P	P	P	P	P
Potentially adverse condition 2					
Potential for such phenomena as thermally induced fractures, the hydration or dehydration of mineral components, brine migration, or other physical, chemical, or radiation-related phenomena that could be expected to affect waste containment or isolation.	P	P	NP	P	NP
Potentially adverse condition 3					
A combination of geologic structure, structure, geochemical and thermal properties, and hydrologic conditions in the host rock and surrounding units such that the heat generated by the waste could significantly decrease the isolation provided by the host rock as compared with pre-waste-emplacement conditions.	NP	NP	NP	NP	NP
MAJOR CONSIDERATION 2: COMPLEXITY OF ENGINEERING MEASURES REQUIRED TO ENSURE WASTE CONTAINMENT AND ISOLATION					
Potentially adverse condition 1					
Rock conditions that could require engineering measures beyond reasonably available technology for the construction, operation, and closure of the repository, if such measures are necessary to ensure waste containment or isolation.	NP	NP	NP	NP	NP
MAJOR CONSIDERATION 3: SIGNIFICANT FLEXIBILITY IN HOST-ROCK DIMENSIONS TO ENSURE ISOLATION					
Favorable condition 1					
A host rock that is sufficiently thick and laterally extensive to allow significant flexibility in selecting the depth, configuration, and location of the underground facility to ensure isolation.	P	NP	NP	P	NP

[a] Key: NP = for the purpose of this comparative evaluation, the favorable or potentially adverse condition is not present at the site; P = for the purpose of this comparative evaluation, the condition is present at the site.

[b] Analyses supporting the entries in this table are presented in Chapter 6 of the environmental assessment for each site.

results to date indicate that impacts from alteration or dehydration are not significant if the carnallite is under confining pressure.

At the Deaf Smith site, repository-induced temperature increases in the salt would contribute to creep effects like those at Davis Canyon. The rate of salt creep is expected to be higher at the Deaf Smith site than at Davis Canyon. The potential for creep-related disturbances to the interbeds and aquifers above the repository adds complexity at the Deaf Smith site.

At the Hanford site, repository-induced temperature increases may alter the permeability of the rock mass, through changes in fractures. It will also increase the in situ stresses in the vicinity of the excavations, possibly resulting in a readjustment of the rock mass and alterations in the local hydrologic regime. The rates of hydrochemical reactions among the various components will increase with the addition of heat. This is expected to have a positive effect on the isolation capabilities of the Hanford site.

At the Richton site, the effect of the repository-induced temperature increase on salt creep is expected to enhance the isolation capability of the site. The rate of salt creep at the Richton Dome is expected to be similar to that at the Deaf Smith site. The absence of stratification and the higher purity of the salt at Richton Dome should result in a less-anisotropic mechanical response to the temperature increase. The Richton Dome has a low brine content, and therefore minimal effects from brine migration are expected. Thermally induced uplift could affect the caprock (gypsum) over the dome, but modeling results indicate that such uplift is not expected to adversely affect the isolation capability of this site.

At Yucca Mountain, the problems associated with repository-induced heat are negligible, primarily because the underground facilities are in the unsaturated zone. The thermal pulse will modify the permeability of existing fractures since thermal expansion decreases the permeability of the rock mass, which in turn reduces the potential for new fractures. The Yucca Mountain site has some rock-mass heterogeneities that could cause an undetermined, but probably not adverse, response to heat (from both the variability of the content of lithophysae and the regions in which the tuff has been welded to different degrees). Although only preliminary measurements from surrounding strata are available, the rock stresses are not expected to be increased to unacceptable levels by the thermal response.

Complexity of engineering measures. This consideration includes in situ characteristics and conditions that could require engineering measures beyond reasonably available technology to ensure waste containment and isolation. Engineering measures relate directly to the qualifying condition through the specification that reasonably available technology is to be used to meet the requirements of the engineered-barrier system. It is derived from the first potentially adverse condition. The major contributing factors to this consideration are the uncertainty about the durability of man-made sealing material after closure and the effects of the in situ environment on engineered-barrier performance (e.g., the effects of brine on the disposal container). Complexity of engineering methods is considered less important than repository-induced heat effects because of the greater potential of heat effects to impair the isolation capabilities of the site. A summary of the evaluation for each site follows.

The sealing of boreholes and shafts at Davis Canyon is not expected to require complex engineering methods. The processes of sealing a repository in salt can be accomplished with technology developed in the salt-mining industry. With regard to interactions between the waste and the host rock, brines at Davis Canyon, if present, could accelerate the corrosion of the waste package.

Like Davis Canyon, the Deaf Smith site is not expected to require complex engineering methods. The site is expected to require particularly careful sealing to isolate the shaft from the Ogallala aquifer. The repository can be sealed by technology developed in the salt-mining industry from experience in drilling in the Palo Duro Basin. Interactions between the brine that may be present and the waste packages could accelerate the corrosion of the waste package, which could diminish the containment capabilities of the engineered-barrier system.

The ability to properly seal shafts and boreholes in basalt and to confirm the long-term effectiveness of seals are major concerns at Hanford. In particular, the sealing of the overlying aquifers from the repository horizon will require additional engineering measures to effectively isolate the waste. With regard to interactions of the various components of the engineered-barrier system, the expected presence of a geochemically reducing environment after closure and the sorptive properties of the secondary minerals formed in fractures in basalt are likely to enhance the containment and isolation capability at Hanford.

At the Richton site, shafts through the overlying saturated sediments and the caprock can be sealed by using technology similar to that used in mines in other salt domes. The sealing of the repository is not expected to require complex engineering measures. Interactions between the brine that may be present in the Richton Dome and the waste package could accelerate the corrosion of the waste package, which could diminish the containment capabilities of the engineered-barrier system.

At Yucca Mountain, the host rock is unsaturated; furthermore, construction experience at the Nevada Test Site shows that technology for borehole and shaft seals is readily available. In addition, since the seals will be required to perform only as well as the overall rock-mass permeability, long-term seal performance requirements are not particularly demanding. With regard to the interactions of the various components of the engineered-barrier system, the expected rock and geochemical conditions are favorable.

<u>Flexibility</u>. This consideration pertains to flexibility in determining the depth, configuration, and location of the underground repository. It relates to the qualifying condition because flexibility in locating the repository at a site increases the favorability of the site with respect to the qualifying condition. Added flexibility in locating the repository will help avoid geologic features or anomalies that could adversely affect the isolation capabilities of the site. Even after requirements for preclosure flexibility have been satisfied, added flexibility may still be necessary to satisfy this postclosure consideration in terms of the depth of excavations, the orientations of drifts and their intersections, and the location of

seals. A greater volume of host rock could provide isolation capability over and above the degree deemed minimally acceptable. On this basis, the contribution of flexibility to waste isolation is less than that of the other two considerations for this guideline. A summary of the evaluation for each site follows.

The host rock at Davis Canyon is expected to offer significant flexibility in that the available thickness appears to be several times greater than the required thickness. In addition, the potential host rock extends laterally underground for many kilometers. The presence of significant interbeds, impurities, gases, and structural features and their potential for adverse effects on flexibility are not yet well defined at this site.

At the Deaf Smith site, numerous interbeds may limit the vertical flexibility of locating a repository with respect to isolation considerations. In contrast, the host rock is expected to extend laterally for a considerable distance. The presence of impurities, brines, gases, and structural features and their potential to adversely affect flexibility are not yet well defined.

The Hanford site appears to offer restricted vertical but extensive horizontal flexibility with respect to isolation considerations. The thickness of the basalt can vary significantly over short distances, and the predictability of host-rock thickness is considered to be uncertain because of a limited data base.

The Richton site provides significant vertical flexibility and adequate lateral flexibility. Unfavorable internal structures within the salt dome could be encountered during site characterization; if present, they would diminish the flexibility for locating underground facilities at this site.

The host rock at Yucca Mountain offers significant vertical flexibility, but lateral flexibility is restricted by minor faults, shallow overburden, or site anomalies. The lateral homogeneity of the potential host rock outside the primary repository area has not been established.

Summary of comparative evaluation

Yucca Mountain is the most favorable site on the basis of the two most important considerations. It is expected that the response of the host rock to the heat loading of the repository would have an overall favorable effect. Furthermore, the long-term seal-performance requirements at Yucca Mountain are not expected to be very demanding. Although the flexibility for locating the underground facility is limited at Yucca Mountain, this does not outweigh the favorability of the other more important considerations.

The Davis Canyon and the Richton sites are next in favorability for the rock-characteristics guideline. At Davis Canyon, the repository-induced temperature increase is expected to improve the performance of the site by increasing the rate of salt creep, which would seal the underground openings by reconsolidating the salt backfill. However, the impact of the brine migration toward the heat source needs to be assessed. The sealing of boreholes and shafts at Davis Canyon is not expected to require complex engineering methods. Davis Canyon is also expected to offer significant flexibility in locating the repository because of its lower brine content. The Richton site is more favorable than Davis Canyon for the repository-induced heat consideration. Richton is less favorable than Davis Canyon and Yucca Mountain on the basis of the major consideration for the complexity of engineering methods because of potential problems with sealing the repository from the overlying sediments and caprock. The Davis Canyon and the Richton sites are equally favorable with respect to host-rock flexibility. On the basis of these comparisons, Davis Canyon and Richton are approximately equal in favorability under this guideline.

Hanford is somewhat less favorable than the Yucca Mountain, the Davis Canyon, and the Richton sites for this guideline. Although Hanford is very favorable with respect to the effects of repository-induced heat, it may require complex engineering methods because of potential difficulties in sealing the overlying aquifers from the repository horizon. There has been little experience in sealing hard-rock mines to the degree that will be required for the repository. Hanford also appears to offer restricted vertical flexibility with respect to isolation considerations.

The Deaf Smith site is considered to be somewhat less favorable with regard to the rock-characteristics guideline. It is the least favorable site for the major consideration of repository-induced heat because of more-extensive interbeds. It is also the least favorable site under the third major consideration because the presence of interbeds limits its vertical flexibility. However, these considerations are not likely to significantly affect the ability of the site to contain or isolate waste.

7.2.1.4 Climatic changes

The qualifying condition for the climatic changes guideline is as follows:

> The site shall be located where future climatic conditions will not be likely to lead to radionuclide releases greater than those allowable under the requirements specified in §960.4-1. In predicting the likely future climatic conditions at a site, the DOE will consider the global, regional, and site climatic patterns during the Quaternary Period, considering the geomorphic evidence of the climatic conditions in the geologic setting.

Major consideration

On the basis of the qualifying, favorable, and potentially adverse conditions for this guideline (see Table 7-4), one major consideration is identified that influences the favorability of the sites with respect to the qualifying condition: the effect of future climatic changes on the ability of the site to isolate waste. Contributing factors include Quaternary climatic cycles and the in situ conditions at a site. The major consideration is directly related to the qualifying condition through the consideration of

Table 7-4. Guideline-condition findings by major consideration--climatic change[a,b]

Condition[c]	Davis Canyon	Deaf Smith	Hanford	Richton Dome	Yucca Mountain
Favorable condition 1					
A surface-water system such that expected climatic cycles over the next 100,000 years would not adversely affect waste isolation.	P		P	P	P
Favorable condition 2					
A geologic setting in which climatic changes have had little effect on the hydrologic system throughout the Quaternary Period.	NP	NP	NP	NP	NP
Potentially adverse condition 1					
Evidence that the water table could rise sufficiently over the next 10,000 years to saturate the underground facility in a previously unsaturated host rock.	NA	NA	NA	NA	NP
Potentially adverse condition 2					
Evidence that climatic changes over the next 10,000 years could cause perturbations in the hydraulic gradient, the hydraulic conductivity, the effective porosity, or the ground-water flux through the host rock and the surrounding geohydrologic units, sufficient to significantly increase the transport of radionuclides to the accessible environment.	NP	NP	NP	NP	NP

[a] Key: NP = for the purpose of this comparative evaluation, the favorable or potentially adverse condition is not present at the site; P = for the purpose of this comparative evaluation, the condition is present at the site.

[b] Analyses supporting the entries in this table are presented in Chapter 6 of the environmental assessment for each site.

[c] All the conditions in this table are associated with one major consideration: the effect of climatic changes on the ability of the site to isolate the waste.

climatic changes that may affect waste isolation. It is derived from the two favorable conditions and the two potentially adverse conditions. A summary of the evaluation for each site follows.

Evaluation of sites with respect to the major consideration

At the Davis Canyon site, climatic changes during the Quaternary Period are thought to have increased precipitation by as much as 120 percent. Increased precipitation during the Pleistocene may have increased recharge rates and flow through hydrostratigraphic units as well as rates of erosion and dissolution. Estimates of increased precipitation are based on regional data that cover the last 13,000 years and site-specific geomorphic data. Although it is uncertain by how much increased precipitation affected the hydrologic system, it does not appear that changes of the same magnitude would adversely affect waste isolation. To establish bounding cases for the potential effects of increased precipitation on the hydrologic system, a simple worst-case assumption was made in which increased precipitation raises the water table to the ground surface in the Abajo Mountains. The resulting hydraulic gradient between the Abajo Mountains and the Colorado River is not significantly greater than the present maximum apparent hydraulic gradient estimated from hydrologic tests. Preliminary estimates of the rates of erosion and dissolution during the Quaternary Period, if projected into the future, would not affect the isolation capability of the host rock, because no significant changes in flow parameters, such as porosity or permeability, have been identified in the Quaternary Period. Preliminary estimates of the maximum rates of incision over the next 100,000 years are approximately 40 meters (132 feet). Although increased rates of incision may alter the surface-water system, increased incision at the surface is not expected to affect the integrity of a repository at a depth of 885 meters (2,900 feet).

At the Deaf Smith site, regional data indicate that lower temperatures and increased effective moisture occurred during the Pleistocene. The Quaternary record suggests cyclical increases in precipitation during pluvial cycles. Increases in precipitation during future pluvial conditions would increase surface-water ponding and growth of vegetation. The increased vegetation would tend to decrease the rates of erosion, though localized increases in erosion could occur near escarpments. Although these climatic changes would change the surface-water system, they are not expected to reduce the waste-isolation capabilities of the host rock. Potential effects of Quaternary climatic cycles on the hydrologic system include changes in the rates of recharge and increased rates of dissolution at salt margins. Increased recharge to the upper hydrostratigraphic unit would result in an increase in the hydrologic gradient between this unit and the underlying units, but models of this process show no significant effect in the underlying units for more than 10,000 years. Although the data are insufficient to quantify the effects of these changes on the hydrologic system, there is no evidence to suggest that Quaternary climatic changes had a significant effect on the ground-water system.

At the Hanford site, if glacially induced catastrophic floods recurred, they would alter the present surface-water system by increasing runoff, the rates of erosion, and ponding. The net effect of catastrophic flooding would be sediment aggradation. These changes in the surface-water system would be short-lived and are not expected to significantly affect the confined aquifers of the Grande Ronde basalts. If glaciation were to recur, the major adverse effects would be increased recharge from meltwater and catastrophic flooding. Increased recharge may be expected to cause some rise in the potentiometric surfaces of shallow aquifer systems, but the transient nature of increased recharge is such that significant long-term effects on the confined aquifers of the Grande Ronde basalts are not expected.

For the Richton site, the data are insufficient to quantify the effects of future climatic changes on the surface-water system. However, regional data suggest that, if the climate returned to a glacial maximum, increased precipitation would slightly increase erosion and ground-water recharge. During the late Wisconsinian glaciation, the sea level in the Gulf of Mexico was 100 to 130 meters (330 to 430 feet) below the present mean sea level. This regional change in base level, combined with regional uplift, resulted in stream entrenchment. Geomorphic evidence in the region suggests that stream entrenchment in major rivers was on the order of 30 meters (100 feet). This would have little effect on the deep confined ground-water system around the Richton Dome. A future interglacial cycle accompanied by a melting of the ice sheets equivalent to Pleistocene interglacials could cause a rise in sea level of 5 to 10 meters (16 to 32 feet). An equivalent rise in sea level would not inundate the surface of the site, which is at least 50 meters (164 feet) above the mean sea level. Thus, the analysis of regional data suggests that future climatic changes would not affect the surface-water or the ground-water systems to the extent that the isolation capabilities of the site would be affected.

Analysis of data on the effects of climate changes in the vicinity of Yucca Mountain suggests that surface-water systems changed little during the Quaternary Period and are not expected to change significantly in the next 10,000 years. The present surface-water system was established by early Quaternary time. It is unlikely that the maximum probable climatic change, from arid to semiarid conditions, would cause a significant change in the present drainage system. Climatic data suggest that Quaternary climatic changes had the following effects on the ground-water system: increased recharge; increased elevation of, and gradients in, the water table; and upgrade shifts in discharge points. Data from the region suggest that the effects of these changes were minor. One exception may be the effect of increased recharge on the hydrologic system, though the magnitude of the increased recharge has not yet been quantified.

If pluvial conditions were to occur, increased recharge may have a significant effect on the ground-water flux and may raise the level of the water table. Preliminary modeling of increases in the water table during a full pluvial cycle, assuming a 100-percent increase in precipitation, suggests a maximum rise of 130 meters (427 feet). Such a rise in the water table would not saturate the repository. Furthermore, considering the various sources of uncertainty in the model--such as the method used to simulate recharge, the assumption that the response of the water table is instantaneous, and the use of a two-dimensional model to simulate three-dimensional flow--the prediction of a 130-meter rise in the water table is uncertain and may not be realistic. It is unlikely that increased recharge from a return to pluvial conditions would significantly increase radionuclide transport to the assessible environment.

Summary of the comparative evaluation

The available data suggest that the Davis Canyon, Deaf Smith, Hanford, and Richton sites are equally favorable with respect to the major consideration and the guideline on climatic changes. At these sites changes in the surface-water system over the next 100,000 years are not expected to adversely affect isolation capabilities. Climatic changes during the Quaternary Period may have had minor effects on the ground-water systems. In the next 10,000 years, none of these sites is expected to undergo climatic changes that would decrease the ability of the natural barriers to isolate the waste.

The Yucca Mountain site is less favorable than the other sites because future climatic changes may produce a significant increase in recharge to the geohydrologic system. Assuming an eventual return to pluvial conditions, preliminary modeling suggests that increased recharge may increase the ground-water flux, decrease the ground-water travel time, and increase the elevation of the water table. The potentially increased flux, combined with a substantial rise in the water table, introduces greater uncertainty in assessing the potential effects of future climatic changes on the Yucca Mountain site. However, climatic conditions during the next 10,000 years would not be likely to significantly increase radionuclide releases to the accessible environment.

7.2.1.5 Erosion

The qualifying condition for erosion is as follows:

> The site shall allow the underground facility to be placed at a depth such that erosional processes acting upon the surface will not be likely to lead to radionuclide releases greater than those allowable under the requirements specified in §960.4-1. In predicting the likelihood of potentially disruptive erosional processes the DOE will consider the climatic, tectonic, and geomorphic evidence of rates and patterns of erosion in the geologic setting during the Quaternary Period.

Major consideration

On the basis of the qualifying, favorable, and potentially adverse conditions for this guideline (see Table 7-5), one major consideration is identified that influences the favorability of the sites with respect to the qualifying condition: the effects of erosional processes on waste isolation. The major consideration is derived from the three favorable conditions and the two potentially adverse conditions and evaluates effects of erosional processes on waste isolation. It is directly related to the qualifying condition through emphasis on the ability to isolate waste.

Table 7-5. Guideline-condition findings by major consideration--erosion[a,b]

Condition[c]	Davis Canyon	Deaf Smith	Hanford	Richton Dome	Yucca Mountain
Favorable condition 1					
Site conditions that permit the emplacement of waste at a depth of least 300 meters (984 feet)below the directly overly ground surface.	P	[illegible]	P	P	NP
Favorable condition 2					
A geologic setting where the nature and rates of the erosional processes that have been operating during the Quaternary Period are predicted to have less than 1 chance in 10,000 over the next 10,000 years of leading to releases of radionuclides to the accessible environment.	P	P	P	P	P
Favorable condition 3					
Site conditions such that waste exhumation would not be expected to occur during the first 1 million years after repository closure.	P	P	P	P	P
Potentially adverse condition 1					
A geologic setting that shows evidence of extreme erosion during the Quaternary Period.	NP	NP	NP	NP	NP
Potentially adverse condition 2					
A geologic setting where the nature and rates of geomorphic processes that have been operating during the Quaternary Period could, during the first 10,000 years after closure, adversely affect the ability of the geologic repository to isolate the waste.	NP	NP	NP	NP	NP

[a] Key: NP = for the purpose of this comparative evaluation, the favorable or potentially adverse condition is not present at the site; P = for the purpose of this comparative evaluation, the condition is present at the site.

[b] Analyses supporting the entries in this table are presented in Chapter 6 of the environmental assessment for each site.

[c] All of the conditions in this table are associated with one major consideration: effects of erosional processes on waste isolation.

Contributing factors include the depth of waste emplacement, evidence of extreme erosion during the Quaternary Period, the potential for uncovering the waste, and the assessment of future erosion rates and geomorphic processes on the basis of the climatic, tectonic, and geomorphic evidence of erosion rates and patterns during the Quaternary Period. These factors cannot be evaluated individually to make a judgment on the qualifying condition; they must be evaluated together. It is for this reason that only one major consideration is identified. A summary of the evaluation for each site follows.

<u>Evaluation of sites in terms of the major consideration</u>

At Davis Canyon, the host-rock unit (salt cycle [illegible]) is estimated to occur at a depth of approximately 885 meters (2,900 feet). During the Quaternary Period, erosion in the candidate area has been almost continuous, though long-term rates of incision are not thought to be extreme. Stream erosion is predicted to erode no more than approximately 3 meters (12 feet) below the present ground surface in 10,000 years. Streams in the region have been predicted to erode up to 240 meters (800 feet) into their present channels (using long-term incision rates) during the first million years after repository closure. The Quaternary geologic record indicates that geomorphic processes should not adversely affect the ability of the repository to isolate the waste. This includes a preliminary assessment of the eastward propagation of the graben systems west of the site. Considering the planned depth of the repository, present knowledge suggests that it is highly unlikely that erosion will lead to releases of radionuclides to the accessible environment in the next 10,000 years.

At the Deaf Smith site, the host rock is in Unit 4 of the Lower San Andres Formation, where the top of the unit is 700 to 760 meters (2,300 to 2,500 feet) below the surface. No evidence is recorded of extreme erosion at the site. Extrapolation from a relatively high river-incision rate in Holocene time shows erosion to a depth of 63 meters (210 feet) in the next 10,000 years. Projections of average Quaternary conditions indicate that erosion of 100 meters (330 feet) would occur over the next 1 million years. Projections of Quaternary erosional conditions indicate that the waste would remain isolated after 10,000 years. Considering the planned depth of the repository, it is unlikely that erosion will lead to releases of radionuclides to the accessible environment in the next 10,000 years.

At the Hanford site, the depth to the Cohassett flow top is 869 to 943 meters (2,850 to 3,093 feet). The site does not show evidence of extreme erosion during the Quaternary Period. Because the depth of erosion is geomorphically controlled by base level, future incision is limited to depths above the minimum sea level. Past glacially induced sea-level changes indicate that erosion at the site could proceed no further than about 440 meters (1,443 feet) above the top of the candidate horizon. The depth of the candidate horizon and the geologic setting of the site are such that the waste would not be expected to be uncovered during the first million years after repository closure. There is little chance, if any, of erosion leading to a release of radionuclides to the accessible environment over the next 10,000 years.

At the Richton site, the waste would be emplaced at a depth of 646 meters (2,119 feet). No evidence of sustained extreme erosion during the Quaternary Period is found in the geologic setting of the site. The geomorphic processes that have been in operation during the Quaternary Period have resulted in a long-term erosion rate of 1.2 meters (4 feet) per 10,000 years. This rate would result in the removal of 120 meters (394 feet) of material in 1 million years, leaving 526 meters (1,718 feet) of material over the repository. The chance of erosion removing the entire thickness of overdome sediments is much less than 1 in 1 million. Thus, it is very unlikely that erosion over the next 10,000 years would lead to any radionuclide releases to the accessible environment.

At Yucca Mountain, the minimum thickness of the overburden above the repository would be about 230 meters (750 feet). For about 50 percent of Yucca Mountain, the overburden is more than 300 meters (984 feet). Average stream-incision rates during the past 300,000 years have not been extreme, and there has been little change in the patterns of erosion at the site during the Quaternary Period. On the basis of average stream-incision rates, the shallowest portion of the repository is expected to remain buried much longer than 1 million years. Over a period of 10,000 years, erosional processes would be expected to remove only 1 meter (3 feet) of overburden. The probability that erosion would induce a loss of isolation is less than 1 in 1 million over the next 10,000 years. Thus, although the Yucca Mountain site does not meet the favorable condition on the depth of emplacement, it appears that the probabilities of erosion causing a loss of isolation are lower than those considered credible in EPA regulations (40 CFR Part 191).

Summary of the comparative evaluation

At all the sites, the underground repository can be placed deep enough to protect it from erosional processes acting on the surface. The predicted rates of erosion are low at all five sites. All waste-emplacement horizons are too deep for credible geomorphic processes to adversely affect the performance of the repository. Although the rates of erosion vary from site to site, the variation is not significant. None of the sites is expected to erode to such an extent that the waste would be uncovered during the first 1 million years. It is also very unlikely that erosion at any of the sites would result in releases of radionuclides during the first 10,000 years. Therefore, all sites are approximately equivalent with respect to the erosion guideline.

7.2.1.6 Dissolution

The qualifying condition for postclosure dissolution is as follows:

> The site shall be located such that any subsurface rock dissolution will not be likely to lead to radionuclide releases greater than those allowable under the requirements specified in §960.4-1. In predicting the likelihood of dissolution within the geologic setting at a site, the DOE will consider the evidence of dissolution

within that setting during the Quaternary Period, including the locations and characteristics of dissolution fronts or other dissolution features, if identified.

Major consideration

On the basis of the qualifying, favorable, and potentially adverse conditions for this guideline (see Table 7-6), one major consideration is identified that influences the favorability of the sites with respect to the qualifying condition: evidence of host-rock dissolution during the Quaternary Period. This major consideration is influenced by several contributing factors, such as the solubility of the host rock under nonextreme geologic and hydrologic conditions, unusual ground-water chemistry, and evidence of significant dissolution during the Quaternary Period. The consideration is directly related to the qualifying condition through concern about the disruption of the natural and engineered barriers by the dissolution of the host rock. Such disruption would result in the potential for exceeding the radionuclide-release limits set by the NRC and the EPA. A summary of the evaluation for each site follows.

Evaluation of sites in terms of the major consideration

The Davis Canyon site is 16 kilometers (10 miles) from the nearest known or potential dissolution feature. Although data on the rate of migration of dissolution fronts in the Paradox Basin are not available, the rates estimated for other basins suggest that a dissolution front would not reach the site for at least 10,000 years. However, it should be noted that the use of such an extrapolation technique increases the level of uncertainty in this estimate. Other known and suspected dissolution features in the area include the Lockhart Basin, 19 kilometers (12 miles) to the north; Beef Basin, 22 kilometers (14 miles) to the southwest; the Needles Fault Zone, 18 kilometers (11 miles) to the west; and the Shay/Bridger Jack/Salt Creek graben system, 16 kilometers (10 miles) to the south. Data derived from field mapping and geophysical logging near the site have not revealed features that would indicate Quaternary dissolution. However, the saline ground waters of the overlying Honaker Trail Formation and the underlying Leadville Formation are thought to indicate past or continuing dissolution of the salt in the Paradox Formation.

The Deaf Smith site is somewhat further from active dissolution fronts than Davis Canyon. Dissolution at or above the repository level is known to occur 103 kilometers (64 miles) to the west, 29.8 kilometers (18.5 miles) to the north and 118 kilometers (73 miles) to the east of the Deaf Smith site. The rates of migration for these dissolution fronts have been calculated from data on the level of salinity in streams. These data suggest that the most rapid rate of migration for the dissolution fronts is 0.98 meter (3.2 feet) per year for the eastern front, while the northern front is migrating at a rate of 0.0008 meter (0.0024 foot) per year. The rate of dissolution for the western front is expected to be even lower. These calculations are based on the assumption that the dissolution front is uniform, which could underestimate the actual rate of dissolution. Within the basin, interior dissolution is evident in the uppermost salt sequence beneath the High Plains aquifer, as indicated by data from dissolution wells. However, the rate of

Table 7-6. Guideline-condition findings by major consideration--dissolution[a,b]

Condition[c]	Davis Canyon	Deaf Smith	Hanford	Richton Dome	Yucca Mountain
Favorable condition					
No evidence that the host rock within the site was subject to significant dissolution during the Quaternary Period.	P		P	P	P
Potentially adverse condition					
Evidence of dissolution within the geologic setting--such as breccia pipes, dissolution cavities, significant volumetric reduction of the host rock or surrounding strata, or any structural collapse--such that a hydraulic interconnection leading to a loss of waste isolation could occur.	P	P	NP	P	NP

[a] Key: NP = for the purpose of this comparative evaluation, the favorable or potentially adverse condition is not present at the site; P = for the purpose of this comparative evaluation, the condition is present at the site.

[b] Analyses supporting the entries in this table are presented in Chapter 6 of the environmental assessment for each site.

[c] All of the conditions in this table are associated with one major consideration: effects of dissolution processes on waste isolation.

dissolution is very slow and has been estimated to be 0.000064 meter (0.000021 foot) per year. No dissolution fronts near the Deaf Smith site or in the interior basin are expected to intersect the repository horizon in less than 100,000 years.

The rock at the Hanford site consists of minerals that are not readily soluble, and significant dissolution leading to radionuclide releases from the site is not considered credible. It is highly unlikely that dissolution will occur along fractures within the repository during or after the thermal phase to the extent that the permeability of the fracture system will increase. The permeability of the fracture system will probably decrease because of the alteration of glass and the formation of clays and zeolites within the fractures.

The Richton site has no topographic depressions over the salt dome, and limited data suggest that the Tertiary sediments overlying the dome are laterally continuous. There are two relatively small, closed circular depressions just off the eastern flank of the dome that appear to be the result of near-surface processes; however, at this time, their origin is uncertain. Samples of ground water from a shallow fresh-water aquifer reveal possible saline anomalies on the south side of the dome (downgradient of the dome). These anomalies were identified on the basis of a very limited number of boreholes; therefore, the origin of the high salinity level in the water of the upper aquifer is unknown at this time. Possible origins for the salinities include salt-dome dissolution, variability of aquifer conditions, and artificial contamination.

The Yucca Mountain site is composed of rock whose minerals are not readily soluble, and significant dissolution leading to radionuclide releases from the site is not considered credible. It is highly unlikely that dissolution will occur along fractures within the repository during or after the thermal phase to the extent that the permeability of the fracture system will increase.

Summary of comparative evaluation

Hanford and Yucca Mountain are the most favorable sites for the dissolution guideline because the host rocks and surrounding unit consist of minerals that are not readily soluble.

The Davis Canyon, Deaf Smith, and Richton sites are less favorable. Available data suggest that dissolution probably occurred at each salt site during the Quaternary Period, but the rates of dissolution are too low to lead to a loss of waste isolation. There is, however, considerable uncertainty associated with these rates because of the limited data base for each site.

7.2.1.7 Tectonics (postclosure)

The qualifying condition for postclosure tectonics is as follows:

> The site shall be located in a geologic setting where future tectonic processes or events will not be likely to lead to radionuclide releases greater than those allowable under the requirements specified in §960.4-1. In predicting the likelihood of potentially disruptive tectonic processes or events, the DOE will consider the structural, stratigraphic, geophysical and seismic evidence for the nature and rates of tectonic processes and events in the geologic setting during the Quaternary Period.

Major consideration

On the basis of the qualifying, favorable, and potentially adverse conditions for this guideline (see Table 7-7), one major consideration is identified that influences the favorability of the sites with respect to the qualifying condition. This major consideration concerns estimates and projections of igneous activity and tectonic processes over the next 10,000 years and the effect of these processes on radionuclide releases. It is directly related to the qualifying condition through the evaluation of radionuclide releases attributed to potential tectonic phenomena. It is derived from the favorable condition and the six potentially adverse conditions.

The contributing factors for this major consideration include evidence of tectonic or igneous activity during the Quaternary Period, the likelihood for the next 10,000 years of tectonic and igneous events that could alter the regional ground-water-flow system, the historical record of seismicity, the correlation of earthquakes with tectonic features, evidence of Quaternary tectonic processes (especially at the repository site), and the potential effects of tectonic and igneous events on the repository. The rates of igneous and tectonic activities cannot be evaluated individually; these conditions must be evaluated together to determine their impact on the total isolation system, and therefore only one major consideration was identified for this guideline. A summary of the evaluation for each site follows.

Evaluation of sites in terms of the major considerations

In the geologic setting of the Davis Canyon site, Quaternary uplift has averaged less than 0.60 meter (2 feet) per 1,000 years. Although no surface faults have been identified at the site, Quaternary faulting may be present in the vicinity of the site at Shay Graben. These faults, however, may be related to salt dissolution rather than tectonism. These faults do not trend toward the site, nor have preliminary investigations shown any surface faults at the site. No known igneous activity has occurred within the geologic setting in the last 2 to 3 million years. No earthquakes have been observed within the site, but the historical record of seismicity is limited. The Paradox Basin has been classified as a relatively low seismic hazard region. However, there is a possibility that the south Shay Graben fault may be capable of producing an earthquake larger than any observed in the geologic setting. The geologic record does not show that any natural impoundments on

Table 7-7. Guideline-condition findings by major consideration-tectonics (postclosure)[a,b]

Condition[c]	Davis Canyon	Deaf Smith	Hanford	Richton Dome	Yucca Mountain
Favorable condition 1					
The nature and rates of igneous activity and tectonic processes (such as uplift, subsidence, faulting, or folding), if any, operating within the geologic setting during the Quaternary Period would, if continued into the future, have less than 1 chance in 10,000 over the first 10,000 years after closure of leading to releases of radionuclides to the accessible environment.	P	[illegible]	P	P	NP
Potentially adverse condition 1					
Evidence of active folding, faulting, diapirism, uplift, subsidence, or other tectonic processes or igneous activity within the geologic setting during the Quaternary Period.	P	P	P	P	P
Potentially adverse condition 2					
Historical earthquakes within the geologic setting of such magnitude and intensity that, if they recurred, could affect waste containment or isolation.	NP	NP	NP	NP	NP
Potentially adverse condition 3					
Indications, based on correlations of earthquakes with tectonic processes and features, that either the frequency of occurrence or the magnitude of earthquakes within the geologic setting may increase.	P	NP	P	NP	P
Potentially adverse condition 4					
More-frequent occurrences of earthquakes or earthquakes of higher magnitude than are representative of the region in which the geologic setting is located.	NP	NP	NP	NP	NP
Potentially adverse condition 5					
Potential for natural phenomena such as landslides, subsidence, or volcanic activity of such magnitudes that they could create large-scale surface-water impoundments that could change the regional ground-water flow system.	NP	NP	NP	NP	NP
Potentially adverse condition 6					
Potential for tectonic deformations--such as uplift, subsidence, folding, or faulting--that could adversely affect the regional ground-water flow system.	NP	NP	NP	NP	NP

[a] Key: NP = for the purpose of this comparative evaluation, the favorable or potentially adverse condition is not present at the site; P = for the purpose of this comparative evaluation, the condition is present at the site.

[b] Analyses supporting the entries in this table are presented in Chapter 6 of the environmental assessment for each site.

[c] All of the conditions in this table are associated with one major consideration: nature and rates of tectonic processes and igneous activity that may affect waste isolation.

the scale necessary to cause large changes in the regional ground-water-flow system occurred in the geologic setting. Regional uplift will not affect the physical integrity of the repository and will be too small to significantly modify ground-water-flow systems in the next 10,000 years. Reactivation of the basement faults beneath the site is possible, but it is doubtful that displacements large enough to propagate these features through the ductile rocks of the Paradox Formation would occur in the next 10,000 years. In general, tectonic data indicate that the likelihood of disruptive tectonic events is very low and suggest that igneous or tectonic activity at the Davis Canyon site could not lead to radionuclide releases greater than regulatory limits after repository closure.

At the Deaf Smith site, data were collected by reviewing published literature and conducting preliminary field surveys. There is no evidence of igneous activity during the Quaternary Period at the Deaf Smith site. The nearest igneous activity during the Quaternary occurred about 160 kilometers (99 miles) west of the site, outside the geologic setting. Quaternary tectonic processes were probably negligible near the site. Regional uplift or subsidence is not recognized, but the possibility that these processes occurred on a small scale during the Quaternary Period has not been ruled out. The site is located in a region of low seismicity. Quaternary faulting and folding of a tectonic (or seismogenic) nature are not recognized in the Palo Duro Basin. No large damaging earthquakes have occurred in the geologic setting during the period of the historical record. The terrain of the site and its vicinity is flat and would not be affected by natural phenomena large enough to cause large-scale surface-water impoundments. Small amounts of uplift or subsidence are not likely to adversely affect the regional ground-water flow over the next 10,000 years. Some uncertainty exists because site-specific information on subsurface faulting has yet to be fully evaluated. However, the likelihood of disruptive tectonic events affecting any releases of radionuclides after closure is thought to be extremely low.

For the Hanford site, preliminary estimates of the rates of tectonic deformation suggest low long-term average rates of strain. Volcanism in the Columbia River Basalt Group ceased approximately 6 million years ago. Although Quaternary volcanism has occurred in the western Columbia Plateau, it appears to be more closely related to volcanism in the Cascades. There are faults within the Columbia Plateau that are interpreted to have been active during the Quaternary Period. Seismic activity has been monitored at Hanford since 1969, but detailed seismic monitoring at the proposed repository depth is only beginning. Some of the faults in the geologic setting could be associated with earthquakes larger than the historical maximum. Available data do not permit the precise determination of slip and recurrence rates for specific faults; however, on the basis of current knowledge, earthquakes near the site would be relatively small, with long recurrence rates for larger events (a magnitude greater than about 5.5). Earthquakes are not currently associated with mapped geologic structures, nor do hypocenters align in a manner that suggests unmapped, buried, or steeply dipping faults occur in the Pasco Basin. It does not appear that natural phenomena or tectonic deformations would create large-scale surface-water impoundments that would cause significant changes in the regional ground-water-flow system.

Although the rate of deformation at Hanford does not appear to be significant enough to affect the release of radionuclides, there is considerable uncertainty because microearthquake swarms have been observed in the basalt during the past 16 years, though no swarms have occurred recently in the basalt at the site. The potential effects of microearthquake swarms on system performance (including the ground-water-travel time, system geochemistry, and waste-package integrity) suggest that the likelihood of tectonic phenomena affecting the site's ability to isolate waste over the next 10,000 years is very low.

At the Richton site, the evidence from the geologic setting suggests that no igneous activity and only minor tectonic activity occurred during the Quaternary Period. The principal active tectonic process during the Quaternary Period is regional uplift. Diapirism does not appear to have occurred at the Richton Dome. There has been no igneous activity in or near the Mississippi salt basin since the Cretaceous Period (about 60 million years ago). There is no evidence of Quaternary seismogenic fault movement in the geologic setting, and the infrequent seismic activity that does occur is low in magnitude. The nearest known earthquake epicenter is 75 kilometers (45 miles) away. The region has no large surface-water impoundments from tectonic or igneous processes. Projections of uplift based on Quaternary data suggest that its rates are too low (0.01 meter per 1,000 years) to adversely affect the regional ground-water-flow system during the next 10,000 years. On the basis of the Quaternary record, future tectonic processes and events are not likely to be disruptive, and the likelihood of disruptive tectonic events is very low.

Much of the background data for the evaluation of tectonic activity at Yucca Mountain has been developed through many years of study related to nuclear weapons testing at the Nevada Test Site. The assessment of future tectonic processes is uncertain and difficult for Yucca Mountain. There is evidence that volcanism and faulting occurred in the vicinity of the site during the Quaternary Period. In addition, the seismicity of the region is not understood well enough to rule out the possibility of large earthquakes (magnitude of 7 or greater) occurring in the region after closure. According to previously published estimates of recurrence intervals, regional return periods for earthquakes with a magnitude of 7 or greater are probably on the order of 25,000 years. At present, a preliminary conclusion could be made that the north-trending faults at the site should be considered potentially active, even though the absence of fault scarps and the low level of seismic activity suggests they are not active. The geologic setting of Yucca Mountain is not yet well enough understood to preclude the possibility of future earthquakes larger than those that have occurred at or near the site.

The formation of large-scale surface-water impoundments by natural phenomena like landslides, subsidence, or volcanic activity is not likely in the area of Yucca Mountain. There is also a very small potential for tectonic deformation at the site of a magnitude that would affect the regional ground-water flow. On the basis of available information, it appears unlikely that volcanic events or future tectonic processes and events would adversely affect the containment and isolation capabilities of the repository, although numerical probabilities have not been determined for most processes. This conclusion is based on the moderate (although uncertain) probabilities of tectonic events, the likelihood that the ground-water travel time is long and the flux is low, the selection of waste-emplacement areas away from recognizable fault zones, the structural integrity of the waste package, and the geochemical characteristics of the site.

Summary of comparative evaluation

The most favorable sites with respect to the postclosure tectonics guideline are Davis Canyon, Deaf Smith, and Richton. Although the Davis Canyon site appears to have a higher rate of tectonic activity near the site (as indicated by potential Quaternary faulting), there is a very low likelihood that tectonic events could lead to releases at any of these sites, and none show evidence of igneous activity in the geologic setting. Active faulting may also be present in the geologic setting of Davis Canyon, but no surface faults have been identified at the site, and seismic and geologic evidence qualitatively suggests that the region will be stable over the long term. The available data suggest that there is very little likelihood of disruptive tectonic or igneous events during the next 10,000 years at all three sites. Both the Deaf Smith and the Richton sites have experienced no igneous activity and insignificant tectonic activity during the Quaternary Period. There are no known Quaternary seismogenic faults in either geologic setting, and the level of seismicity at both sites appears to be very low.

Hanford is slightly less favorable than the salt sites for this guideline. There is some evidence that deformation is occurring within the basalts at Hanford, but the pattern of deformation qualitatively matches the pattern of known seismicity, suggesting that earthquakes and rupture planes would be relatively small and recurrence times generally long. There is some uncertainty because microearthquake swarms in the basalts have been observed during the past 16 years. In addition, no microearthquakes (nonswarm) have been observed within the repository site at the depth of the basalts. The likelihood of tectonic phenomena affecting the ability of the site to isolate waste over the next 10,000 years is very low.

Yucca Mountain is less favorable than the other sites. Quaternary faults are present within 1 to 6 kilometers of the site. Their effects on the potential for ground motion and on ground-water flow need to be assessed. The likelihood of volcanism may be high enough for volcanism to be considered in performance assessment. However, the effects of igneous and tectonic activity on system performance (qualifying condition) at Yucca Mountain are not expected to lead to radionuclide releases greater than those allowed by regulation. This assessment accounts for ground-water flux and travel time, waste emplacement away from recognized fault zones, the structural integrity of the waste package, and the geochemical characteristics of the site.

7.2.1.8 Human interference

The potential for human interference after the closure of the repository requires an analysis of (1) the natural resources at or near a site, addressing historical, current, and future exploration for, and uses of, these resources, and (2) site ownership and control. Evaluations of these two separate technical guidelines are provided below.

7.2.1.8.1 Natural resources

The qualifying condition for natural resources is as follows:

> This site shall be located such that--considering permanent markers and records and reasonable projections of value, scarcity, and technology--the natural resources, including ground water suitable for crop irrigation or human consumption without treatment, present at or near the site will not be likely to give rise to interference activities that would lead to radionuclide releases greater than those allowable under the requirements specified in §960.4-1.

Major considerations

On the basis of the qualifying, favorable, and potentially adverse conditions for this guideline (see Table 7-8), three major considerations are identified that influence the favorability of the sites. In decreasing order of importance, they are (1) evidence of subsurface mining, resource extraction, and drilling sufficient to affect containment and isolation; (2) potential for foreseeable human activities that could affect containment and isolation; and (3) potential for postclosure intrusion for resource extraction. Although the major considerations are listed in decreasing order of importance, the differences in their importance are small, particularly between the second and the third considerations.

Evaluation of the sites in terms of the major considerations

Evidence of subsurface mining, resource extraction, and drilling sufficient to affect containment and isolation. This consideration assesses the potential effects on waste containment and isolation of existing mines and drillholes within the site. Contributing factors include the presence of active and closed mines as well as evidence of deep drilling and related resource extraction. This consideration is derived from the second and the third potentially adverse condition and is the most important major consideration because existing mines or drill holes could act as pathways for radionuclide migration to the accessible environment. A summary of the evaluation for each site follows.

At the Davis Canyon site, existing uranium mines extend to a maximum depth of 11 meters (35 feet) and are restricted to the Chinle Formation, which has been eroded from most of the repository operations area. These existing excavations are not thought to be extensive enough or deep enough to affect the repository. No drilling is known to have occurred within the site. The nearest hydrocarbon-exploration borehole of appreciable depth is 8 kilometers (5 miles) from the boundary of the repository operations area.

There is no subsurface mining at the Deaf Smith site. There are no known wells that penetrate below the Ogallala aquifer and no known hydrocarbon-exploration holes at the site. Deep drilling at the site is unlikely to have occurred in the past.

Table 7-8. Guideline-condition findings by major consideration--natural resources[a,b]

Condition	Davis Canyon	Deaf Smith	Hanford	Richton Dome	Yucca Mountain
MAJOR CONSIDERATION 1: EVIDENCE OF SUBSURFACE MINING, RESOURCE EXTRACTION, AND DRILLING SUFFICIENT TO AFFECT CONTAINMENT AND ISOLATION					
Potentially adverse condition 2					
Evidence of subsurface mining or extraction for resources within the site if it could affect waste containment or isolation.	NP	NP	NP	NP	NP
Potentially adverse condition 3					
Evidence of drilling within the site for any purpose other than repository-site evaluation to a depth sufficient to affect waste containment and isolation.	NP	NP	NP	NP	NP
MAJOR CONSIDERATION 2: POTENTIAL FOR FORESEEABLE HUMAN ACTIVITIES SUFFICIENT TO AFFECT CONTAINMENT AND ISOLATION					
Potentially adverse condition 5					
Potential for foreseeable human activities such as ground-water withdrawal, extensive irrigation, sub-surface injection of fluids, underground pumped storage, military activities, or the construction of large-scale surface-water impoundments--that could adversely change portions of the ground-water flow system important to waste isolation.	NP	NP	P	NP	NP
MAJOR CONSIDERATION 3: POTENTIAL FOR POSTCLOSURE INTRUSION TO EXTRACT RESOURCES					
Favorable condition 1					
No known natural resources that have or are projected to have in the foreseeable future a value great enough to be considered a commercially extractable resource.	NP	NP	NP	NP	P
Favorable condition 2					
Ground water with 10,000 parts per million or more of total dissolved solids along any path of likely radionuclide travel from the host rock to the accessible environment.	P	P	NP	P	NP

8 0 0 0 8 0 9 9 6

Table 7-8. Guideline-condition findings by major consideration--natural resources[a,b] (continued)

Condition	Davis Canyon	Deaf Smith	Hanford	Richton Dome	Yucca Mountain
MAJOR CONSIDERATION 3: POTENTIAL FOR POSTCLOSURE INTRUSION TO EXTRACT RESOURCES (Continued)					
Potentially adverse condition 1					
Indications that the site contains naturally occurring materials, whether or not actually identified in such form that (i) economic extraction is potentially feasible during the foreseeable future or (ii) such materials have a greater gross value, net value, or commercial potential than the average for other areas of similar size that are representative of, and located in, the geologic setting.	P	[illegible]	P	P	NP
Potentially adverse condition 4					
Evidence of a significant concentration of any naturally occurring material that is not widely available from other sources.	NP	NP	NP	NP	NP

[a] Key: NP = for the purpose of this comparative evaluation, the favorable or potentially adverse condition is not present at the site; P = for the purpose of this comparative evaluation, the condition is present at the site.

[b] Analyses supporting the entries in this table are presented in Chapter 6 of the environmental assessment for each site.

Current and past mining or extraction activities in the area of the Hanford site include some quarrying for sand and gravel as well as a small natural gas field that ended production in 1941. The quarries are excavated pits that are generally less than 18 meters (60 feet) deep. The gas field was located approximately 11 kilometers south of the site. No other current or past production of hydrocarbons has been reported within 100 kilometers of the larger Hanford Site. Recent hydrocarbon exploration in the Columbia Plateau has been focused on the sedimentary sequence beneath the basalt; wells drilled to date have been noncommercial, but some natural gas has been recovered. Although methane has been found as dissolved gas in ground water from the Grande Ronde Formation beneath the site, the hydrocarbon potential for this area is speculative at best. Boreholes drilled near the site for purposes other than repository-site evaluation are significantly shallower than the candidate repository horizon and would not affect waste containment or isolation.

At the Richton site, there is no evidence of boreholes, shafts, or other excavations that penetrate the repository horizon within the salt dome. Eight mineral-exploration boreholes have been drilled into salt with a maximum reported penetration of 6.4 meters (21 feet). Within 10 kilometers (6.2 miles) of the dome, 34 sulfur-exploration wells and 32 petroleum-exploration wells have been drilled. The water wells within the area are shallow (less than 366 meters (1,200 feet)) and are drilled into the upper aquifer. The closest fluid-injection wells are at least 4.8 kilometers (3 miles) from the flank of the dome. Waste containment and isolation are not expected to be significantly affected by the presence of shallow boreholes or the potential for increased dissolution associated with the petroleum-exploration wells on the sloping flank of the dome.

There has been no subsurface mining or extraction of resources at Yucca Mountain. There is little likelihood that unknown excavations exist at the site other than shallow prospecting pits. Before the repository investigations began, one borehole had been drilled 7 kilometers (4 miles) southeast of the site (water well J-13), and another had been drilled approximately 15 kilometers (9 miles) to the northeast (water well J-12). There has been no drilling at Yucca Mountain for purposes other than repository-site evaluation.

<u>Potential for foreseeable human activities that could affect containment and isolation</u>. Factors contributing to this consideration include the potential for ground-water withdrawal, irrigation, the injection of fluids, underground pumped storage, and large-scale surface-water impoundments. Changes to the site's ground-water system can directly affect the releases of radionuclides to the accessible environment. This consideration is derived from the fifth potentially adverse condition and is the second most important major consideration. Changes to the site's ground-water system can directly affect the releases of radionuclides to the accessible environment. This consideration is not as important as the first major consideration because it is based on projected, more speculative human activities that may affect isolation, whereas the first consideration is based on existing evidence of resources that could affect isolation.

In assessing the likelihood of postclosure intrusion, the DOE will consider the estimated effectiveness of the permanent markers and records required by NRC regulations in 10 CFR Part 60. Human-intrusion events are considered to be credible only if it is assumed that the monuments provided for in the NRC regulations are permanent enough to serve their intended purpose. Thus, in evaluating this major consideration, the environmental assessments have qualitatively considered the effectiveness of markers and records in reducing the likelihood of human intrusion in the controlled area. A summary of the evaluation for each site follows.

Because of limited potable water and resources within and near the Davis Canyon site, the potential for foreseeable human activities to adversely affect the ground-water-flow system is expected to be very low.

At the Deaf Smith site, good-quality ground water that is suitable for irrigation and domestic use is drawn entirely from the Ogallala aquifer. The ongoing depletion of the Ogallala aquifer will not reverse the downward flow potential at the site. The potential for the subsurface injection of fluids is considered to be low because of the low potential for petroleum development in the future.

At the Hanford site, there is a potential for ground-water withdrawal for irrigation. Insufficient data are available to determine whether such human activities could adversely change portions of the ground-water flow system that are important to waste isolation. However, it is believed that, even if portions of the ground-waste-floor system were to change, there would be no significant effect on waste isolation itself.

At the Richton site, the potential to adversely affect the ground-water-flow system is expected to be very low. Potential human activities are very unlikely to affect ground-water travel through the salt stock; this includes activities that may change fresh-water aquifers. The likelihood of pumped storage in the controlled area is also expected to be very low, considering the permanent markers and records.

Although potable ground water is present at the Yucca Mountain site, future generations are not likely to drill for water from the top of Yucca Mountain, because it would be easier to drill for water in the surrounding areas. Because isolation depends primarily on the thick unsaturated zone, withdrawal of water outside the controlled area would not adversely affect the ground-water system important to isolation.

Potential for postclosure intrusion to extract resources. This consideration includes estimates of, and the potential for, postclosure intrusion for resource extraction. Contributing factors include the presence or indication of resources (including water) at the site, their value, scarcity, and depth, as well as their availability from other sources. This condition is derived from the first and the second favorable conditions and the first and the fourth potentially adverse conditions. This consideration is third in importance because the potential for resources is based on speculative or indirect evidence. Nevertheless, this consideration is significant because exploration for, or the extraction of, resources can create pathways for radionuclides to reach the accessible environment. A summary of the evaluation for each site follows.

Uranium and vanadium deposits are present in the vicinity of the Davis Canyon site, and some production has occurred at the site itself; however, the uranium resources at the site are believed to be less significant than those in other parts of southeastern Utah. In addition, commercial-grade underground potash deposits are present in the vicinity of the site, but they may not be economic because they are located at excessive depths and are less extensive than deposits in other parts of Utah. Small amounts of sand, gravel, and potable water have been extracted in the vicinity of the site. None of these resources has greater potential within the area of the site than outside it. Potential hydrocarbon resources are believed to be significantly smaller within the site than in similar areas outside the site. The ground-water is of poor quality, with the total dissolved solids exceeding 10,000 parts per million.

At the Deaf Smith site, ground water is being extracted from the Ogallala aquifer. The use of this water resource does not pose a threat to the long-term integrity of the repository. Ground water along the likely pathways of radionuclide travel is not suitable for human consumption because it contains dissolved solids at concentration exceeding 10,000 parts per million. The hydrocarbon potential at the site is not considered to be significant, but exploration for oil and gas in the future cannot be discounted. No other mineral resources, such as uranium and construction aggregates, are present in unique quantities at the site. The bedded salt may be considered a halite resource. There are no known concentrations of naturally occurring materials that are not widely available from other sources.

At the Hanford site, there are no known metallic or petroliferous resources that have or are projected to have a value great enough to be commercially extractable. However, there are indications that the site contains ground-water resources and natural gas that may be economically feasible to extract in the foreseeable future. Although hydrocarbon source beds may exist beneath the basalt, there is no evidence to date of significant concentrations of any naturally occurring resources that are unique to the site.

The Richton Dome is the largest of 35 shallow salt domes in the Mississippi salt basin. Because of its size and depth, it is an excellent candidate for underground storage. The purity of the salt (91 percent sodium chloride) also indicates that the dome may be a candidate for salt extraction by solution mining or conventional mining methods. In comparison with other shallow salt domes, the potential for storage or salt extraction at the Richton Dome is above average because of its large size, even though salt is widely available from other sources and the dome's potential use as an underground storage facility is not unique. Commercial hydrocarbon resources are not known to exist at the Richton Dome.

Yucca Mountain has no energy or mineral resources for which extraction is feasible in the foreseeable future. No known resources are present at Yucca Mountain that have greater commercial potential than those in other areas in its geologic setting, nor is there evidence of any significant concentration of potentially valuable resources at Yucca Mountain. The mineral-resource potential of the Yucca Mountain site is considered low. The ground water along likely flow paths of radionuclide travel has less than 10,000 parts per million of total dissolved solids.

Summary of comparative evaluation

On the basis of the three major considerations, Yucca Mountain is the most favorable site; Davis Canyon, Deaf Smith, and Hanford are comparable; and Richton is the least favored site. The differences among the sites, however, are small. This judgment is based on the fact that there is no evidence at any of the sites of subsurface mining, extraction, or drilling sufficient to affect containment or isolation. There is also no evidence at any of the sites of a significant or unique concentration of any naturally occurring mineral or energy resources. It is expected that the use of permanent markers and records will reduce to very low values the likelihood of human intrusion within the controlled area at each of the sites.

The likelihood of any resource occurring at the Yucca Mountain site appears to be very low. The potential use of the deep aquifer outside the controlled area will not affect containment and isolation.

The Davis Canyon, the Deaf Smith, and the Hanford sites are approximately equal in favorability on the basis of the speculative potential for resources. There is a very small potential for the use of the shallow aquifer outside the controlled area at the Hanford site to affect the ground-water-flow system important to isolation.

Richton Dome is the least favorable site because of the speculative potential for resources, the possibility of undetected boreholes, and the potential for using the dome for underground pumped storage.

7.2.1.8.2 Site ownership and control

The purpose of the postclosure guideline on site ownership and control is to help ensure that the repository can function far into the future without adverse human interference. This guideline specifies that the DOE, in accordance with the requirements of the 10 CFR Part 60, is to obtain ownership of, and surface and subsurface rights to, land and minerals within the controlled area of the repository. A similar guideline on site ownership is provided for the preclosure period. The purpose of the preclosure guideline is to ensure that surface and subsurface activities during repository operation will not be likely to lead to radionuclide releases greater than those allowed by applicable regulations.

The DOE has determined that the necessary land area and controls are the same for both the postclosure and the preclosure periods at the five nominated sites. Whichever site is selected, the DOE must obtain ownership as well as surface and subsurface rights before commencing preclosure activities; there is no basis for distinguishing among the sites on their site ownership and control status at the beginning of the postclosure period. Therefore, all sites are considered to be equally favorable for this guideline.

7.2.2 POSTCLOSURE SYSTEM GUIDELINE

The results of preliminary system-performance assessments are described in Section 6.4.2 of each environmental assessment and briefly reviewed here. These preliminary assessments are based on limited geologic, hydrologic, and geochemical information, preliminary conceptual models, and relatively simple analytical techniques. The DOE is therefore not yet prepared to provide assurance that regulatory criteria will be met at any of the sites. These preliminary assessments do, however, appear adequate for evaluating the sites against the postclosure system guideline. However, the different approaches to the evaluation of performance, the preliminary nature of these assessments, and the uncertainties in the parameters on which the analyses are based all limit the ability to compare the sites in the manner required by the implementation guidelines for site comparisons that will support the recommendation of a site for development as a repository. To provide a comparative context for understanding the postclosure system guideline evaluation in Chapter 6, a brief discussion of the evaluation of each of the sites with respect to each of the capabilities addressed by the guideline is presented below.

The guideline addresses the following capabilities of the geologic setting at a site:

1. The capability of the geologic setting at the site to allow for the physical separation of the waste from the accessible environment after closure in accordance with the requirements of the EPA standard in 40 CFR Part 191, Subpart B, as implemented by 10 CFR Part 60.

2. The capability of the geologic setting at the site to allow for the use of engineered barriers to ensure compliance with the requirements of the EPA and the NRC. Two requirements are pertinent here: (1) the time of substantially complete containment (i.e., a period between 300 and 1,000 years); and (2) the limit on the rate of radionuclide releases from the engineered-barrier system (i.e., one part in 100,000 per year of the individual radionuclide inventory or one part in 100,000 per year of the total inventory calculated to be present at 1,000 years after repository closure, whichever is greater).

Capability for waste isolation. The results of the preliminary assessments indicate that the EPA standards would be met at all of the sites. For example, the mean time of ground-water travel from the repository to the accessible environment is expected to be much longer than 10,000 years at each site. On this basis alone, there is little likelihood of any release for 10,000 years or, more specifically, of exceeding the EPA standard for cumulative releases during this period. In fact, the results of the calculations for the preliminary assessments indicate that releases are likely to be negligible for much more than 10,000 years at each site. Similarly, calculations of ground-water quality indicate that the EPA's ground-water protection and individual-protection requirements will be met at each of the sites. For the Hanford site, the calculations show to a high level of confidence that less than 50 curies of iodine-129 and carbon-14--and no other radionuclides--would be released to the accessible environment in 100,000 years. The calculations for Yucca Mountain indicate that less than 100 curies of technetium-99 and negligible quantities of any other radionuclide could be released in 100,000 years. The analyses for the salt sites show no release in 100,000 years under expected repository conditions.

Because of the different characteristics of each of the sites, different approaches to the performance analyses and varying levels of conservatism have been used for each site. For example, the constraint on release due to the slow degradation of the waste form was not taken into account in the analysis of the Hanford site. The analysis of the Yucca Mountain site does not consider the spatial distribution of waste packages throughout the repository, but assumes that the release occurs from a single location in the host rock. Transport and retardation in the saturated zone are not considered in these analyses as well. The margin of conservatism resulting from such assumptions in each case is not known at present. However, it is believed to be sufficient to compensate for the uncertainties in the site data. The preliminary performance assessments do not provide evidence to support a finding that any of the sites would not adequately isolate the waste from the accessible environment.

Requirements for engineered-barrier performance. Preliminary assessments of the engineered-barrier system indicate that this system would meet the regulatory performance objectives at all sites. For example, the analyses of waste-package performance indicate that the container lifetime is expected to exceed the 300- to 1,000-year requirement for substantially complete containment at each site. The expected container lifetime for the Hanford site exceeds 6,000 years. The analysis of the container under the conditions of the Yucca Mountain site gives a lower-bound estimate of 3,000 years and an expected lifetime of 30,000 years. At the salt sites, the lifetime of the container is calculated to be even longer, because it is expected that sufficient water will not be available to cause corrosion failure of the waste package.

For each site, the calculations of the rate of radionuclide release after the failure of the waste package suggest that the criterion for the rate of release from the engineered-barrier system would not be exceeded. At the Hanford site, the release rate for most radionuclides would be well below the regulatory criterion because of the diffusion-limited transport and the limited solubility of these radionuclides in the ground water at the site. For the few radionuclides that are highly soluble, the calculated release rates are less than 4 percent of the release-rate limit.

Without taking into account the solubility of the radionuclides themselves, the fractional release rate calculated for the Yucca Mountain site is 2.5×0^{-9} per year, well below the limit of 1×10^{-5} per year, because of the low rate expected for waste-form dissolution. At the salt sites, since it is expected that the waste packages will last indefinitely, the rate of radionuclide release from the engineered-barrier system is expected to be zero.

Extremely conservative assumptions were used in making these estimates. For example, in all cases the calculations are for releases from the waste package, which is expected to provide an upper bound to the release from the total engineered-barrier system. In addition, any containment offered by the spent-fuel cladding was not taken into account in any of the analyses. In the analysis of the salt sites and of the Hanford site, the slow dissolution of the waste form, which can limit the rate of radionuclide release, was not taken into account. In the analyses of the salt sites and of the Yucca Mountain site, it was assumed that all packages fail simultaneously. Again, the degree of conservatism provided by these assumptions is not known at present. However, the analyses appear to be sufficient to indicate that there is no evidence that the performance criteria for the waste package and other engineered barriers would not be met at each of the nominated sites. Furthermore, the available data and the preliminary analyses based on these data have not identified any conditions or features at any of the sites that would prevent these engineered components from meeting the performance requirements.

The different approaches to the evaluation of performance, the preliminary nature of these assessments, and the uncertainties in the parameters on which the analyses are based all limit the ability to compare the sites in terms of these results. In each case the analyses are very simple. The interactions of the various factors that determine subsystem and system performance are not yet known. Finally, the analyses that can be conducted at present are too simple to address the full range of uncertainties that should be addressed in order to provide an adequate comparison of the sites. Therefore, because of the preliminary nature of these performance assessments, it does not appear that a comparison between and among the sites on the basis of the postclosure system guideline is practicable at present.

7.3 COMPARISON OF SITES ON THE BASIS OF PRECLOSURE GUIDELINES

The preclosure guidelines address (1) preclosure radiological safety; (2) the environmental, socioeconomic, and transportation-related impacts associated with repository siting, construction, operation, and closure; and (3) the ease and cost of repository siting, construction, operation, and closure. Both technical and system guidelines are provided for each of these three categories.

7.3.1 PRECLOSURE RADIOLOGICAL SAFETY

7.3.1.1 Technical guidelines

There are four technical guidelines on preclosure radiological safety: (1) population density and distribution, (2) site ownership and control, (3) meteorology, and (4) offsite installations and operations. The objective of these guidelines is to protect the health and safety of the public and the workers at the repository by keeping exposures to radiation within the limits prescribed by regulations. This section presents a comparative evaluation of the five nominated sites against these guidelines.