information regarding ground water chemistry can be found in USG86, USG84d, USG91b, USG91c, and USG93a.)

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

Alluvial Aquifer

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

Carbonate Aquifer

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

7.1.3 Climate Considerations

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

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

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

7.1.3.1 Past Climate Conditions and Variations

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

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

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

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

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

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

7.1.3.2 Potential Future Climate Conditions

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

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

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

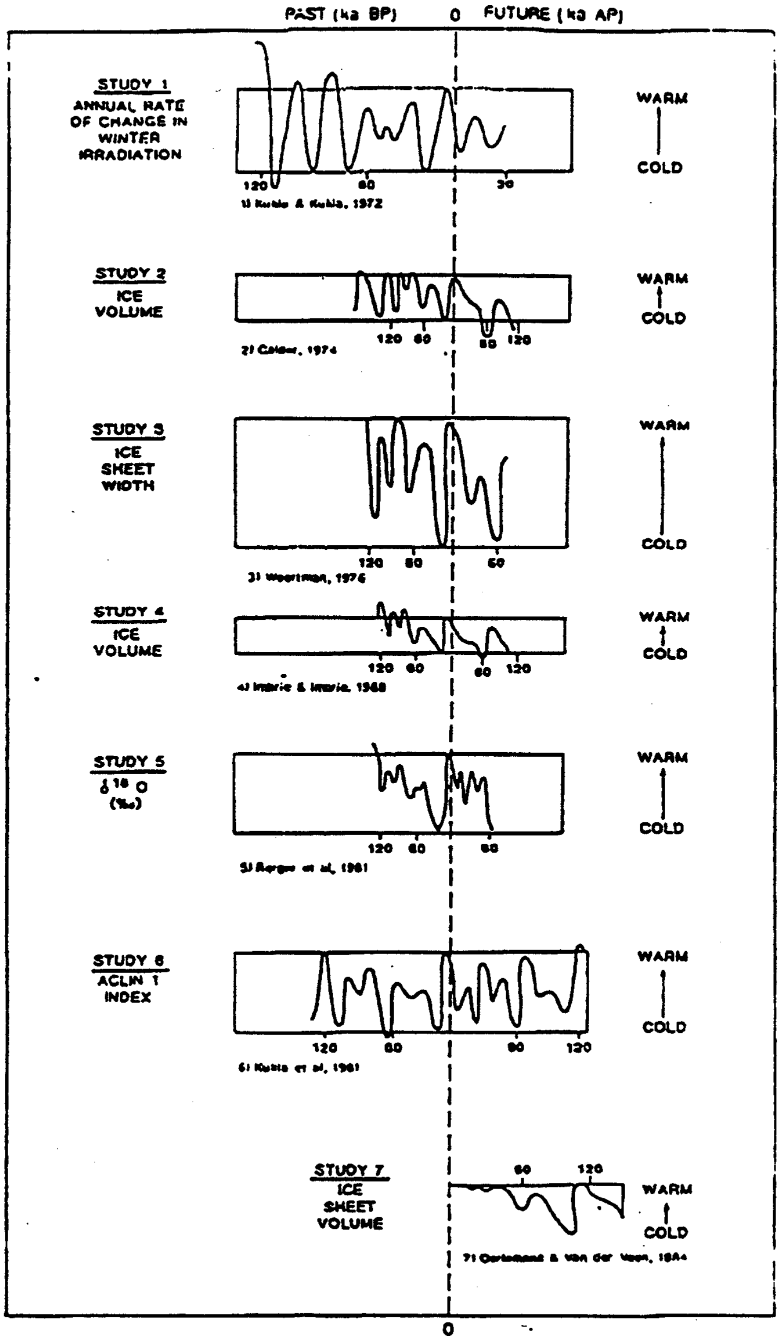

Figure 7-28. Future Climates, Expressed in Terms of Overall Global Temperature Change Future climates, expressed in terms of overall global temperature change, as predicted by seven different models driven by changes in orbital forcing. The boxes on each diagram delimit the last glacial and interglacial extremes. Dates are in years x 10^3. (GOO92)

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

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

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

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

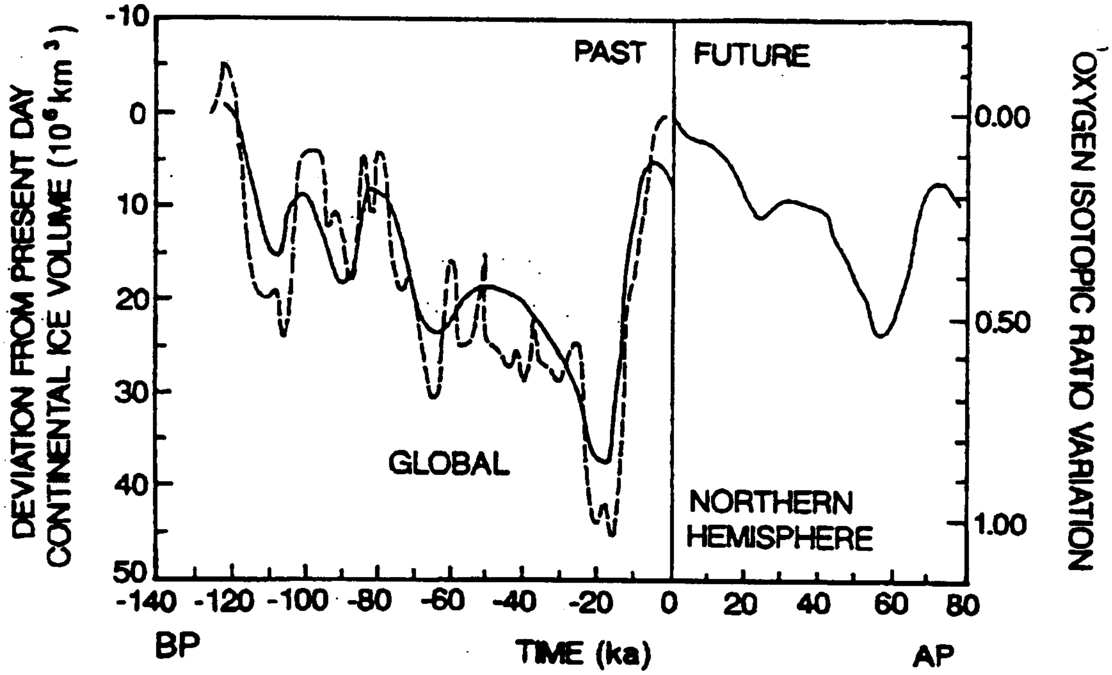

Figure 7-29. Model Simulations of Past and Future Climate Conditions
Model simulations (solid line) of past and future climate conditions, expressed in terms of changing ice volume on the continents, and including anthropogenic greenhouse effects in the immediate future. Dashed line gives past global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

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

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

7.1.3.3 Summary Regarding Climate

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

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

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

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

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

7.2 REPOSITORY CONCEPTS UNDER CONSIDERATION FOR YUCCA MOUNTAIN

7.2.1 Conceptual Repository Systems

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

In response to requirements of the Fiscal Year 1997 Energy and Water Appropriations Act (PL 104-782), the DOE performed a Viability Assessment (VA)[24] for development of a repository for disposal of highly radioactive wastes at Yucca Mountain. The purpose of the VA was to provide policy makers with an estimate of the viability of a repository at the Yucca Mountain site in the time frame required for decision making.

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

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

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

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

- Horizontal emplacement of waste packages in parallel excavated drifts.
- An initial thermal loading on the surroundings corresponding to 85 MTU/acre.
- Emplacement of waste packages only between the Ghost Dance fault and the Solitario Canyon fault.
- Disposal of 63,000 MTU of commercial spent fuel and 7,000 MTU equivalent of various types of defense wastes. A total of 10,500 waste packages would be emplaced, consisting of 7,642 packages of commercial spent fuel and 2,858 packages of defense wastes.
- Disposal in excavated drifts 5.5 m in diameter, with a total of about 107 km of tunnels and drifts in an emplacement area of 740 acres. Drifts would be spaced 28 m apart.
- Packages of commercial spent fuel would contain 21 PWR fuel rod assemblies or 44 BWR assemblies.
- Waste package design features which include, for the commercial spent fuel packages, dimensions of 2-m diameter and 6 m length, with an outer shell of A 516 carbon steel 10 cm thick and an inner shell of corrosion-resistant Alloy 22 that is 2 cm thick.
- Temperature limits of 200°C for the drift walls and 350 ^{0}C for the commercial spent fuel cladding.

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

7.2.2 Design Concepts for Engineered Features of the VA Repository

7.2.2.1 Repository and Surface Facility Layouts

The VA reference design for excavation of tunnels and drifts for emplacement of wastes is shown in Figure 7-30. The repository footprint, which covers about 740 acres, is offset from both the Ghost Dance and Solitario Canyon faults. The footprint is about 1 km wide and 3 km long. This layout resulted from consideration of factors such as potential for fault movement, location of dominant fracture systems in the geologic formations, ease of access during operations, and the heat emissions and temperature limits assumed as the basis for establishing design parameters. The location of the repository within Yucca Mountain is shown in cross section in Figure 7-31.

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

Because of their initial high heat and radiation emissions, emplacement of the waste packages will be done remotely. As previously noted, the VA design temperature limit for the drifts is 200°C; radiation field levels at the surface of the packages would be on the order of 35-60 rem/hour.

7.2.2.2 Waste Package Design

Waste package designs will be tailored to the characteristics of the waste type (commercial spent PWR and BWR fuel; U.S. Navy spent fuel; other DOE-originated spent fuel; vitrified high-level waste; and immobilized surplus plutonium from nuclear weapons). The dominant types of waste

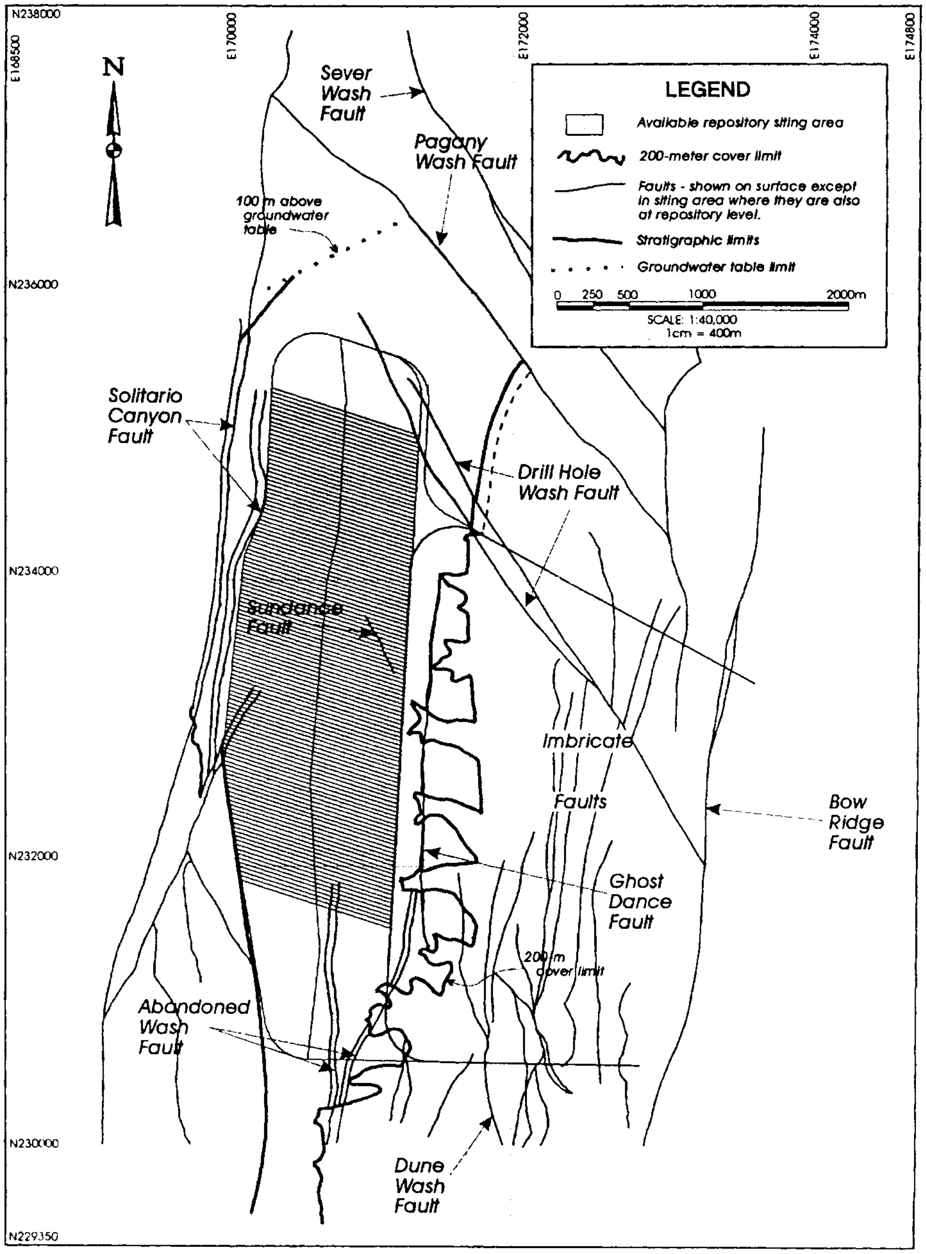

Figure 7-30. Repository Layout for the VA Reference Design (DOE98)

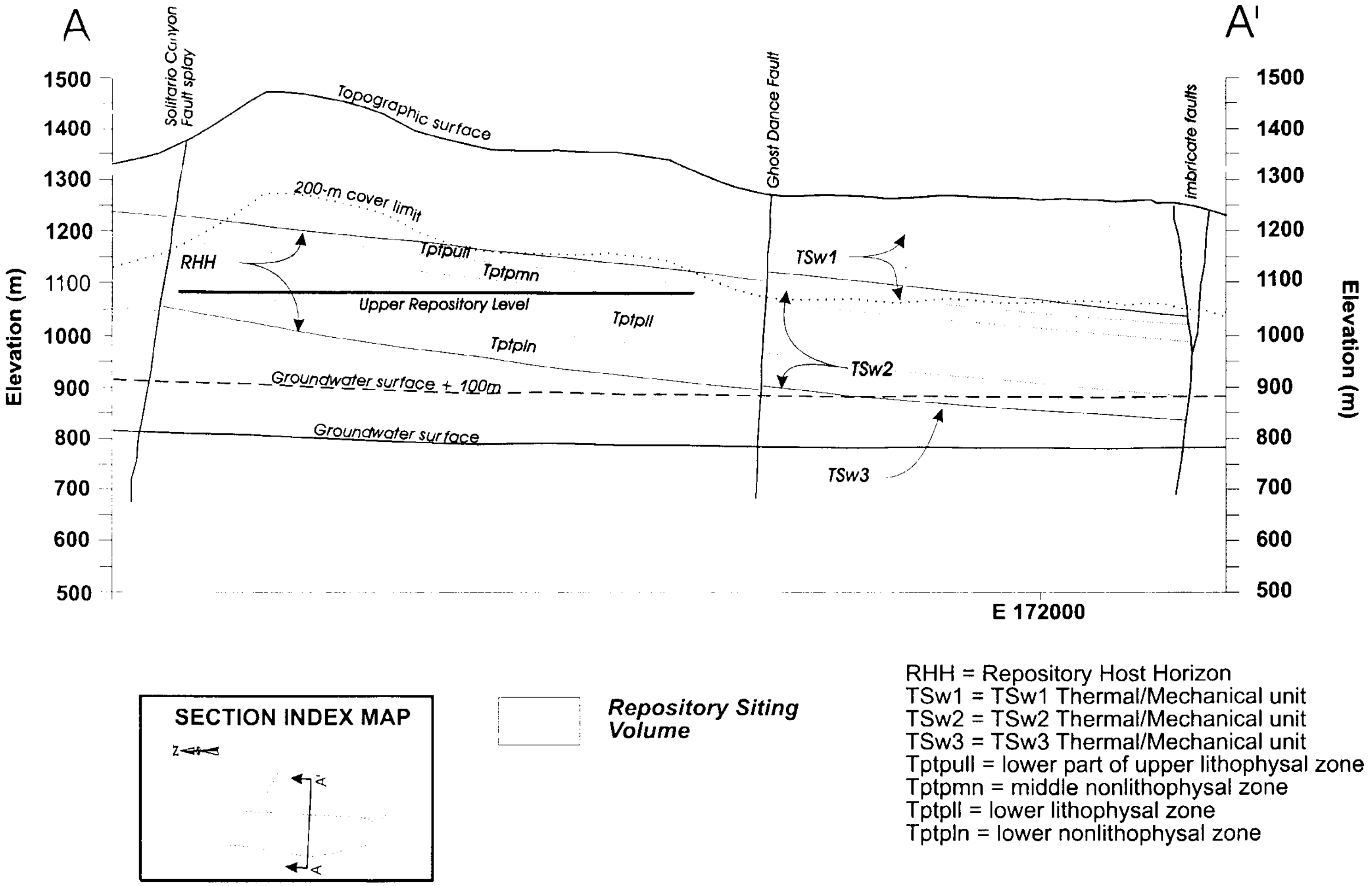

Figure 7-31. Repository Location Within Yucca Mountain (DOE98)

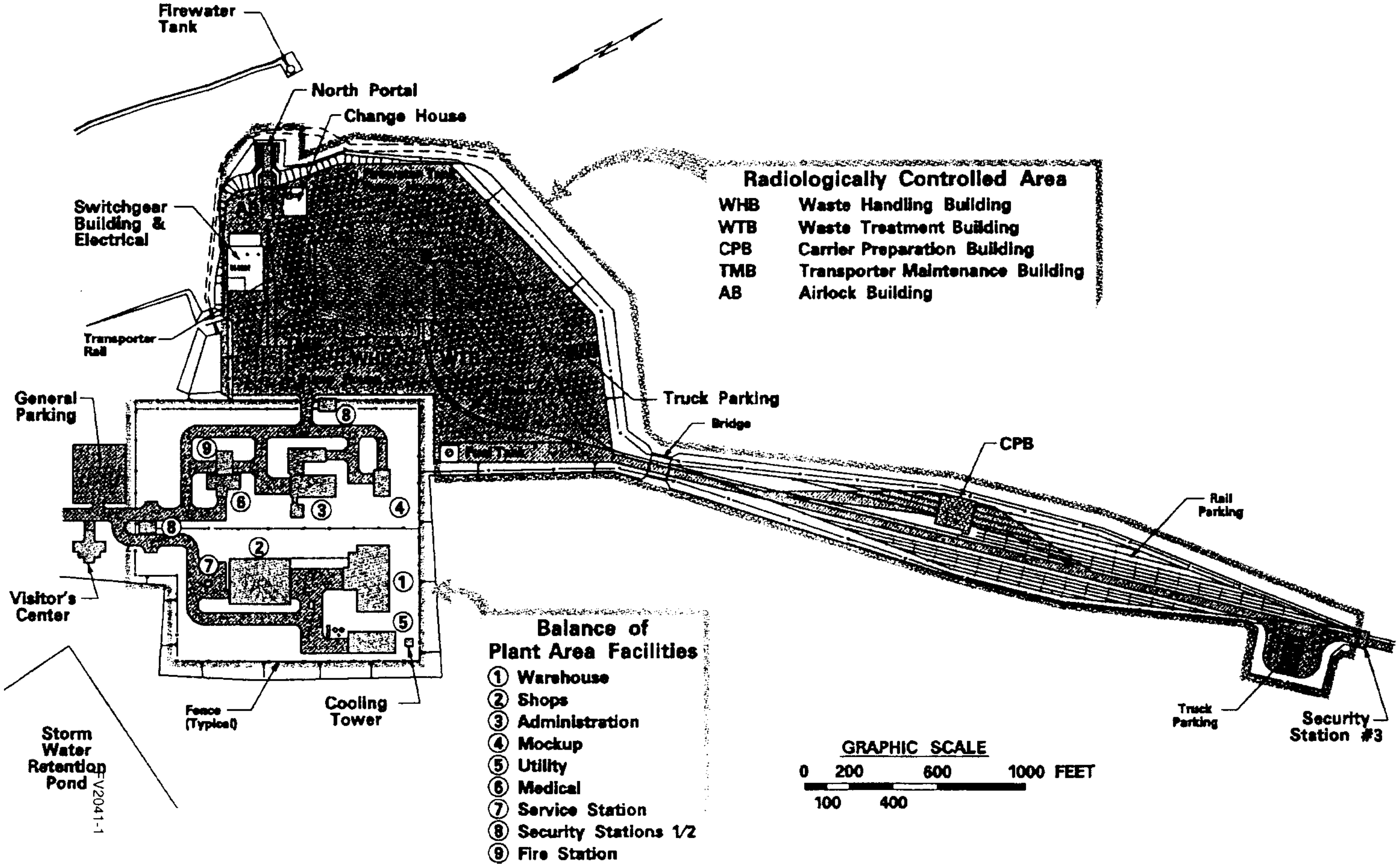

Figure 7-32. North Portal Facilities Layout for the VA Reference Design (DOE98)

packages in the repository will be those for commercial spent PWR and BWR fuel; in the VA reference design, there would be about 7,600 commercial spent fuel packages, two-thirds of which would contain PWR spent fuel and one-third BWR spent fuel. Most of the PWR packages would contain 21 spent fuel assemblies; the BWR packages would contain 44 assemblies (the BWR assemblies are about half the size of the PWR assemblies). Both types of waste packages contain about 10 MTHM.

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

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

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

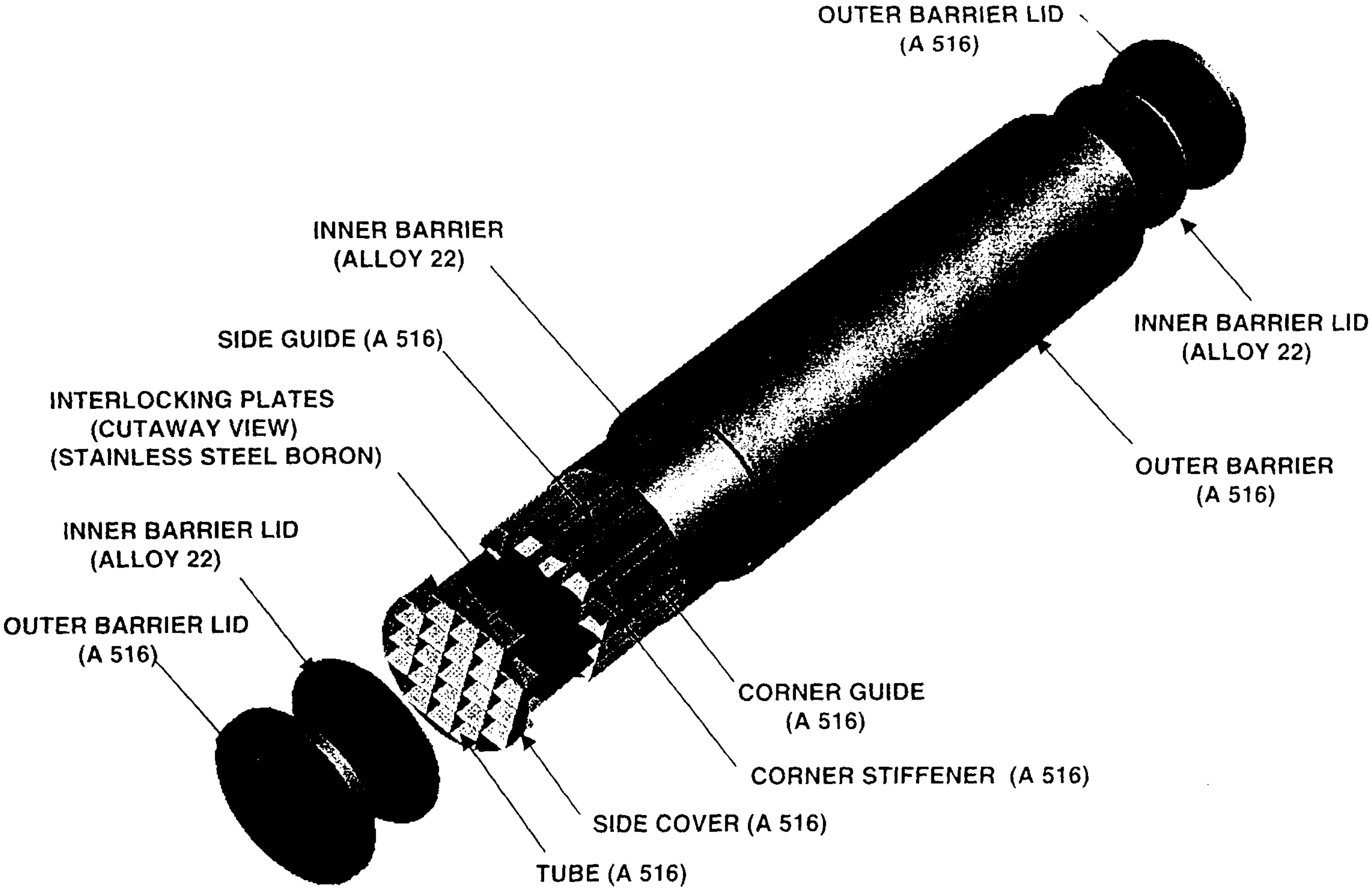

Figure 7-33. 21-PWR Waste Package Design for the VA Reference Design (DOE98)

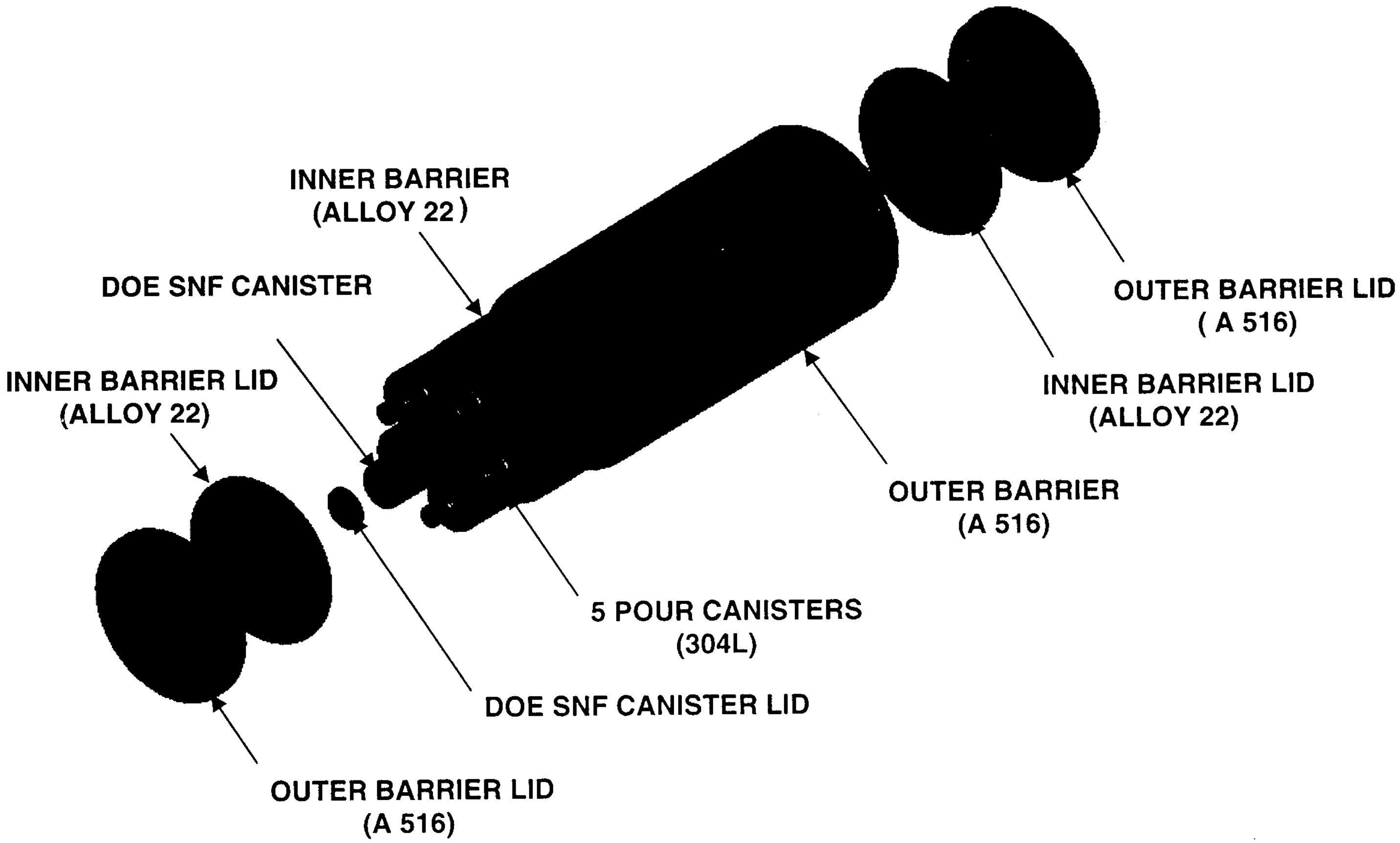

Figure 7-34. Defense HLW Package Design for the VA Reference Design (DOE98)

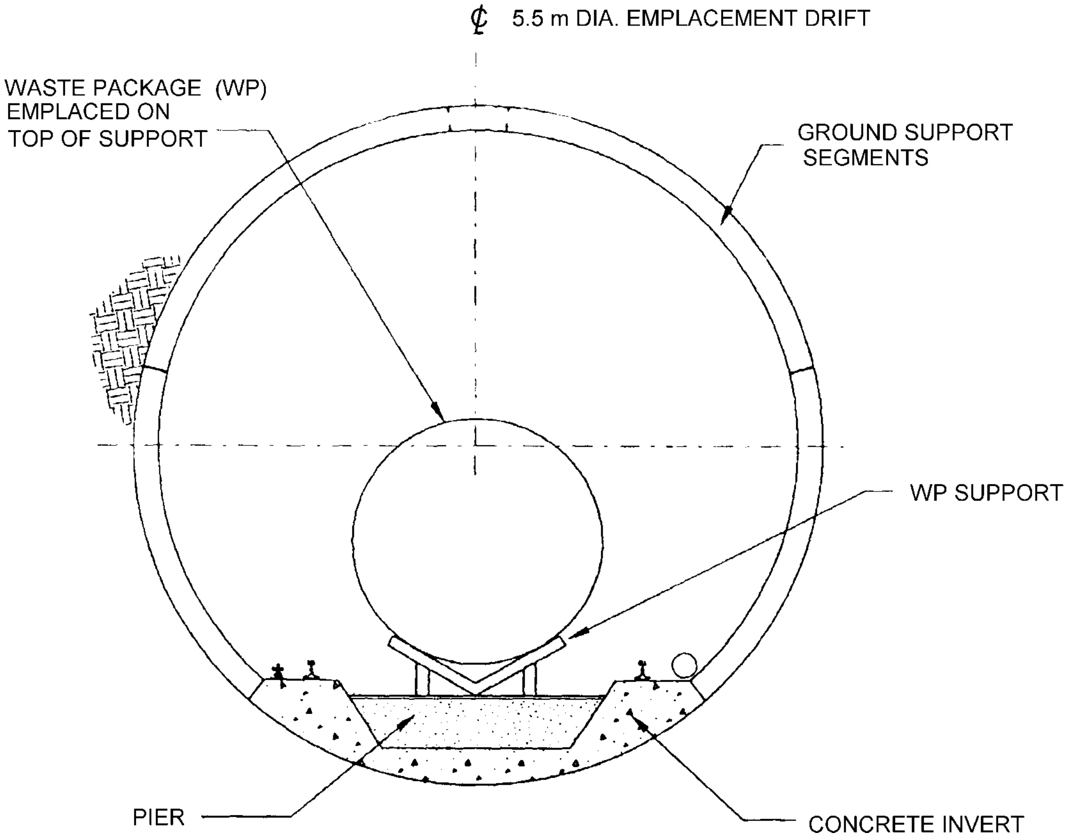

Figure 7-35. Drift Cross-Section for the VA Reference Design (DOE98)

7.2.2.3 Thermal Management Strategy

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

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

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

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

7.2.2.4 Data Sources

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

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

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

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

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

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

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

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

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

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

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

7.2.2.5 Alternative Repository Design Concepts Under Consideration

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

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

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

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

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

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

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

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

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

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

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

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

Design Characteristics	**EDA II**	**Viability Assessment Design**
Areal Mass Loading	60 MTU/acre	85 MTU/acre
Drift Spacing	81 m	28 m
Drift Diameter	5.5 m	5.5 m
Total Length of Emplacement Drifts	54 km	107 km
Ground Support	Steel	Concrete lining
Invert	Steel with sand or gravel ballast	Concrete
Number of Waste Packages	10,039	10,500
Waste Package Material	2-cm Alloy-22 0ver 5-cm stainless steel 316L	10-cm carbon steel over 2-cm Alloy-22
Maximum Waste Package Capacity	21 PWR assemblies	21 PWR assemblies
Peak Waste Package Power (blending)	20% above average PWR waste package power	95% above average PWR waste package power
Drip Shield	2-cm Ti-7	none
Backfill	Yes	none
Preclosure Period	50 years	50 years
Preclosure Ventilation Rate	2 to 10 cubic m/s	0.1 cubic m/s

the principal features of the design is that the time-temperature history of the waste packages is expected to avoid conditions in which the Alloy 22 outer wall would be vulnerable to crevice corrosion.

Repository performance assessment models and parameter values (see Section 7.3) were revised from those used in the VA in accord with the EDA II design parameters and the information emerging from the data acquisition program described in Section 7.2.2.4. The resulting performance assessment, known as the TSPA for Site Recommendation (TSPA-SR) was issued in late 2000. Principle differences between the TSPA-SR and the earlier VA assessment include improved modeling of waste package performance for EDA II design conditions, which reduced emphasis in juvenile waste package failures, and increased emphasis on disruptive events and processes. The primary disruptive issues addressed in the TSPA-SR are igneous activity at the site, and inadvertent human intrusion.

7.3 REPOSITORY SYSTEM PERFORMANCE ASSESSMENTS

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

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

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

DOE's historic TSPA efforts are discussed in Section 7.3.1 and Section 7.3.2. NRC's performance assessments are discussed in Section 7.4, and EPRI's efforts are described in Section 7.5. Results of recent assessments by DOE, NRC, and EPRI are compared in Section 7.6. The most recent DOE TSPA effort, TSPA-SR, is described in Section 7.3.10.

7.3.1 DOE's Historic Performance Assessments

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

The DOE subsequently has conducted TSPA evaluations in 1991 (DOE92), 1993 (DOE94a, DOE94b), 1995 (DOE95b), 1998 (DOE98) and, most recently, for the Site Recommendation (TSPA-SR, TRW00b). Each assessment built on the insights and results of prior assessments, and on the evolving data base and design concepts. Each successive TSPA evaluation added details and features to the models and parameter values in accord with progress enabled by the evolving information base.

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

Because of the difference in the type of radiation protection standards, the results of the TSPA-VA analyses are expressed differently from those of prior analyses. Consistent with a dose-limit standard, the TSPA-VA and TSPA-SR results are expressed as potential doses to receptors, for time periods up to one million years. In contrast, results for the TSPA 1991, 1993, and 1995 analyses were expressed in terms of a Complementary Cumulative Distribution Function

(CCDF), which is an appropriate representation of results for comparison with the cumulative release standards established in the 40 CFR Part 191 regulations.

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

TSPA-91

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

TSPA-93

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

- A three-dimensional stratigraphy for the unsaturated zone which was based on site data
- A saturated zone model in which each geohydrologic unit was discretely modeled
- Assessment of the effect of thermal loading (at levels of 57 and 114 kW/acre) on performance
- Waste package failure models which included aqueous and dry oxidation corrosion, and waste form degradation models which included dissolution and oxidation
- Consideration of two types of waste packages: the thin-walled, small-capacity containers emplaced in boreholes, as envisioned in the Site Characterization Plan (DOE88), and, for the first time, the large-capacity packages emplaced horizontally in drifts

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

TSPA-95

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

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

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

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

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

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

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

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

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

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

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

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

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

7.3.2.1 Repository Design Features for the TSPA-VA

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

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

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

Assumptions That Provide the Basis for Design Parameter Values

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

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

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

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

7,642 CSNF packages in the repository. There will be a total of 2,858 packages of defense wastes, for a repository total of 10,500 waste packages.

- The surface facilities, subsurface facilities, and waste package designs will be based on a reference areal mass loading range of 80 to 100 MTU/acre.
- The temperature of the drift walls will be limited to no more than 200°C (392°F).
- The temperature of the CSNF fuel cladding will be limited to 350°C (662°F).
- The repository's western and eastern boundaries will be between the Solitario Canyon fault and the Ghost Dance fault.

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

Repository Footprint

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

Waste Package Emplacement Configuration

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

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

Waste Package Design

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

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

Design Options

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

Alternative strategies include use of a low emplacement density or long-term cooling before emplacement, either of which would reduce the areal thermal loading and would be intended to reduce performance issues and uncertainties arising from the high temperatures associated with the VA reference design. DOE proceeded to characterize and evaluate some of the options, one of which was chosen as the basis for the design for the Site Recommendation.

7.3.2.2 TSPA Concepts and Methodology

This section presents an overview of TSPA concepts and methodologies that were the basis for DOE's implementation of performance assessment in the TSPA-VA. As previously noted, the TSPA-VA is a snapshot in time of performance evaluation for the VA reference design, data base, and models that were available for the purpose. The TSPA has recently gone through another iteration to become the TSPA for Site Recommendation (TSPA-SR). If the Yucca Mountain project proceeds to the stage of preparing a License Application for a repository at Yucca Mountain, the details of the TSPA for the application would likely be different from those of either the TSPA-VA or the TSPA-SR. Consequently, this section is intended to provide general information on the basic concepts and methodology of TSPA, using TSPA-VA as an example.

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

- Develop and screen scenarios of conditions and factors important to performance. Scenarios address features, processes, and events that can affect repository performance, such as average annual precipitation rates and changes therein.

- Develop analytical models to represent the factors important to performance. The models are usually implemented as computer codes.

- Assign values to performance parameters in the models. Some parameters will be single-valued, such as the density of water at a given temperature; others will have uncertainty ranges because of inherent variability or lack of certain knowledge of the value.

- Implement the models by operating the computer codes.

- Interpret and apply the results for purposes such as identification of additional data needs or assessment of compliance with regulatory standards.

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

- Limit the potential for water to contact the waste packages

- Design the waste package for a long lifetime

- Seek a low rate of release from breached waste packages
- Seek radionuclide concentration reduction during transport through the environment to the location of the dose receptor

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

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

- Precipitation, infiltration, seepage, and dripping are drivers for radionuclide release that bring water to the waste packages
- Waste package humidity, temperature, and chemistry drive the rate of attack on the inner and outer waste package barriers
- The waste package wall is a principal inhibitor of radionuclide release; inhibition of release is also accomplished by the integrity of the spent fuel cladding, resistance to dissolution of the waste forms, and the limited solubility in water of Np-237
- Radionuclide mobility during transit from the repository to and through the environment is aided if the radionuclides are attached to colloids but inhibited if they become sorbed onto surfaces along the flow path
- Transport of radionuclide-bearing water from breached packages brings the radionuclides to the dose receptor location through pathways in the unsaturated and saturated zones
- Dilution during transit and pumping will reduce the radionuclide concentrations in water used by the dose receptor
- Biosphere transport will bring radionuclides into contact with the dose receptor in accord with his/her life style and practices

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

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

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

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

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

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

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

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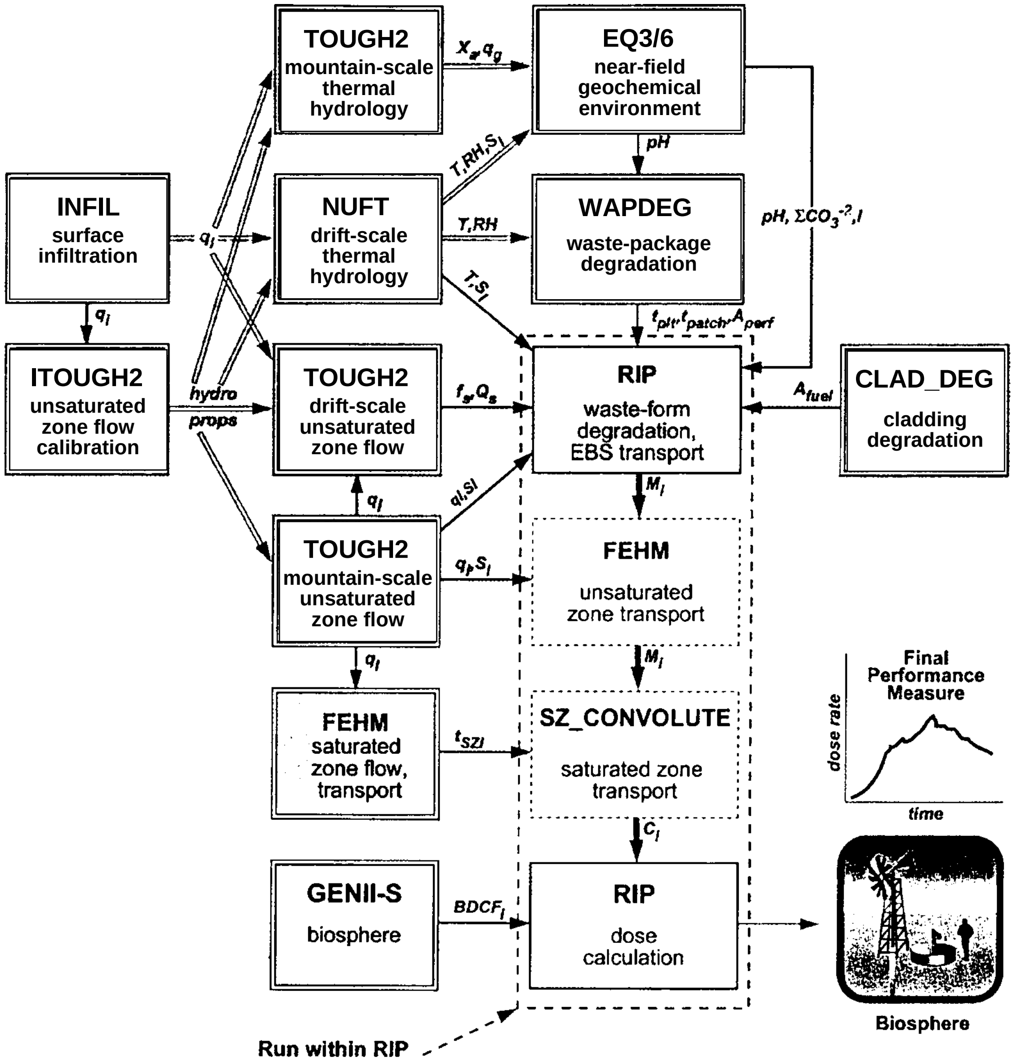

OUTPUT Parameters

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

Legend

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

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

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