TO BE ARGUED ON SEPTEMBER 19, 2003

Case No. 02-1116

IN THE

United States Court of Appeals

FOR THE DISTRICT OF COLUMBIA CIRCUIT

STATE OF NEVADA, *et al.*,

Petitioners,

v.

UNITED STATES NUCLEAR REGULATORY COMMISSION,

Respondent.

PETITION FOR REVIEW FROM FINAL DECISIONS AND ACTIONS OF UNITED STATES NUCLEAR REGULATORY COMMISSION

SUPPLEMENTAL APPENDIX
Volume II

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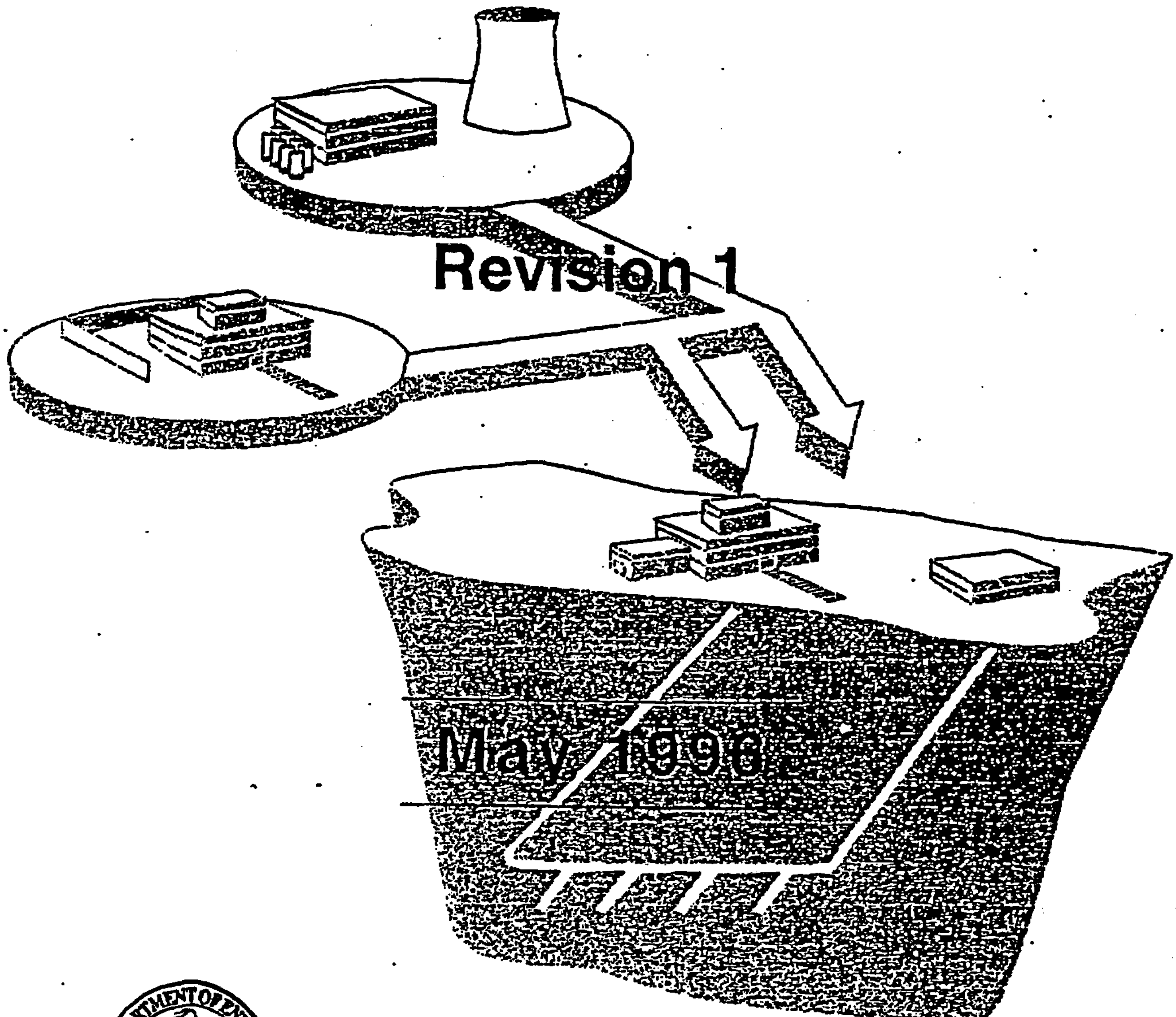
SUPPLEMENTAL APPENDIX VOLUME II INDEX

SAP No.	Date	Document Description	SuppApp#
SAP-27	1996/05/00	Draft "Civilian Radioactive Waste Management Program Plan – Rev. 1" (DOE)	621-623
SAP-47	2001/06/00	Excerpts from the Evaluation of Potential Economic Impacts of 40 C.F.R. PART 197: Public Health and Environmental Radiation Protection Standards for Yucca Mountain, Nevada	624-671

SAP-27

DRAFT

Civilian Radioactive Waste Management Program Plan



Revision 1

May 1996

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Message from the Director

Background

In December of 1994, as the product of an extensive review of the Program, consultation with a broad spectrum of stakeholders, and a comprehensive strategic planning cycle, we published the *Civilian Radioactive Waste Management Program Plan.* That plan outlined an approach to accomplish the principal objectives of the Program with reasonable target dates and at substantially reduced cost compared to earlier estimates. It remained, however, within the statutory and regulatory framework governing the site suitability process for the Yucca Mountain Site Characterization Project and preserved the programmatic expectations and definitions that had evolved from that framework.

The Administration proposed the new program approach in its Fiscal Year 1995 budget request and the Congress approved the funding for the first year of the Program, a 37 percent increase over the previous fiscal year. Utilizing the Fiscal Year 1995 funding, and drawing upon the extensive scientific and analytical work already available, we have made a great deal of progress.

The Yucca Mountain Project completed a total system performance assessment that provides important insights into the critical factors that will affect the ability of the engineered and geologic features of a repository to meet long-term standards of public health and safety. Guided by these insights we are refining a waste containment and isolation strategy that, in turn, will focus the future scientific and engineering work on the critical factors. We will emphasize the scientific data collection and analyses required to confirm the hypotheses underlying the waste isolation strategy and concentrate our near-term design effort on the critical technological requirements of the engineered barriers. Finally, the exploratory tunnel has penetrated the repository formation itself and is beginning to provide solid confirmation of the general theory of the site conditions that has been developed from surface indications, drilling, and seismic work.

With regard to the Program's waste acceptance responsibilities, any future scenario of at-reactor storage, consolidated interim storage, and ultimate disposal will require an extensive transportation effort to remove spent fuel from reactor sites. A new generation of storage and transportation casks and canisters will have to be available to provide a comprehensive ability to service all fuel and all sites, to enhance standardization of equipment and operations, and to improve system-wide economics. In Fiscal Year 1995, the Program continued its work on transportation casks and initiated a major contract intended to make the first high-capacity, comprehensive multi-purpose canister system available to the marketplace by 1998.

SAP-47

EVALUATION OF POTENTIAL ECONOMIC IMPACTS OF 40 CFR PART 197:

PUBLIC HEALTH AND ENVIRONMENTAL RADIATION PROTECTION STANDARDS FOR YUCCA MOUNTAIN, NEVADA

June 2001

3.0 EVOLUTION OF THE YUCCA MOUNTAIN REPOSITORY DESIGN

This chapter describes the evolution of design concepts for a repository at Yucca Mountain that has occurred as a result of site characterization findings, performance assessment results, external reviews, and strategy for dealing with uncertainties. The discussion demonstrates that EPA's standards have not affected the design evolution.

This section describes how the design of a repository for the Yucca Mountain site has evolved since the Site Characterization Plan (SCP; DOE88) was published in 1988. The SCP reference design concept involved vertical emplacement of small, thin-walled canisters, with a design lifetime on the order of 300-1,000 years, into the floor of tunnels excavated in Yucca Mountain. The current design concept calls for horizontal emplacement of large, double-walled waste packages, with a design lifetime of more than 100,000 years (TRW00), into drifts excavated in Yucca Mountain with a tunnel boring machine.

The design evolution has been driven principally by acquisition of site characterization data which showed that the performance of the natural features of the repository system during the regulatory period would be less effective than anticipated when the SCP was issued and data were sparse. It was originally expected that water would flow very slowly, and in limited amounts, through the unsaturated geohydrologic regime, that radionuclides released from the repository and transported by water would be trapped on rock surfaces and pores along the flowpath, and that water would travel relatively slowly through the saturated zone. In contrast to this expectation, site characterization data have demonstrated that water from precipitation infiltrates into the mountain at rates much higher than originally expected; that there are paths for rapid transport of water from the surface to the repository horizon and possibly to greater depths; and that flow in the saturated regime is expected to occur primarily in fractures and with limited dilution of radionuclide concentrations. Potential for radiation doses during the regulatory period is dominated by soluble radionuclides that are mobile and move with the water. The natural features will constrain transport of radionuclides that are insoluble and sorbed onto rock surfaces.

The design evolution also was guided by results of a series of analyses of expected repository performance known as Total System Performance Assessments (TSPA); by DOE/NRC technical exchanges and NRC documents which indicate NRC expectations for licensing reviews; and by external reviews of program documents and status by parties such as the Nuclear Waste Technical Review Board (NWTRB), the NRC staff, and the TSPA Peer Review Panel. A series of formal Expert Elicitations on key performance topics such as waste package degradation also played a significant role in design evolution.

Several stages of design evolution can be identified and associated with the SCP and a subsequent series of TSPA reports. The SCP in 1988 was followed by a series of TSPA evaluations in 1991, 1993, 1995, 1998, and 2000. These evaluations were aimed at providing guidance for site characterization activities and priorities and at exploring the effects of engineered design options on performance. In the 1996-1997 time frame, site characterization data and results of expert elicitations became available and provided the basis for the TSPA evaluations included in the Yucca mountain Viability Assessment (i.e., the TSPA-VA), which was issued in 1998 in response to a mandate by the U.S. Congress. The TSPA-VA was the first performance evaluation for a potential repository design at Yucca Mountain. This assessment has been replaced by the TSPA for Site Recommendation (TSPA-SR), which focuses on the latest repository design. This design was developed as a consequence of findings of the TSPA-VA, as described here.

External and DOE-internal reviews of the TSPA-VA revealed that there were highly significant uncertainties and technical issues associated with the repository design that were the basis for the TSPA-VA. In response to the critiques and suggestions, DOE subsequently developed and adopted the Enhanced Design Alternative (EDA) concept, in which several improved repository designs were evaluated. The selected alternative, known as EDA II, subsequently became the design basis for the most recent TSPA iteration, known as the TSPA for Site Recommendation (TSPA-SR).

Discussion of the design and associated TSPA evolution process is provided below. The current design concept, EDA II, is described in Section 3.4. Discussion of TSPA methodology and results is provided in Section 4. The discussion here shows how the repository design was shaped by the evolving understanding of the site's natural features and the uncertainties involved in projecting repository performance.

3.1 The 1988 Site Characterization Plan

The Nuclear Waste Policy Act of 1982 (NWPA) required each candidate repository site to prepare a comprehensive site characterization plan describing how information would be obtained to determine the site's suitability for disposal of highly radioactive wastes. After enactment of the Nuclear Waste Policy Amendments Act of 1987, which designated Yucca Mountain as the only candidate site to move forward with evaluation of suitability for disposal, DOE issued the SCP for the site in 1988. The document received comprehensive, in-depth review by NRC staff, whose comments, based on the Commission's 10 CFR Part 60 regulations for high-level waste disposal, helped shape the path of site characterization and design.

At the time of publication of the SCP, the site characterization database was highly limited. Expectations of repository performance were based largely on assumptions concerning site features and characteristics. The plans for site characterization activities were designed to obtain data sufficient to assess compliance with existing regulatory standards in the 40 CFR Part 191 and 10 CFR Part 60 regulations. Repository development was subsequently driven by NRC requirements.

3.1.1 Regulatory Framework for the SCP

Under provisions of the NWPA (NWP83), the EPA is to promulgate, for high-level radioactive waste disposal, generally applicable environmental standards for protection of the environment and human health. The NRC is to promulgate regulations to implement the EPA standards and to review the License Application from DOE in order to evaluate compliance with the standards. The EPA regulations were promulgated in 1985 and codified at 40 CFR Part 191; the implementing NRC regulations were codified at 10 CFR Part 60. When the SCP was published in 1988, Part B of the EPA regulations had been remanded by a Federal District court to the Agency for reconsideration. Part B specifies limits on cumulative, long-term radioactivity release from a repository, and also characterizes use of performance assessment to evaluate releases. Although Part B of the 40 CFR Part 191 regulations was being reconsidered by the Agency at the time the SCP was issued, DOE treated the Part B requirements as an operative part of the regulatory framework. Implementation was guided by the Issues Hierarchy (DOE86), which had at the top of the hierarchy, as the overarching issues, the NRC's 10 CFR Part 60 subsystem performance requirements.

The NRC's implementing 10 CFR Part 60 regulations, in addition to adopting the EPA requirements, set performance objectives for specific parts of the repository system. These subsystem performance requirements included:

- Containment of waste within the waste packages must be "substantially complete" for a period of 300 to 1,000 years.
- The rate of radionuclide release (with certain exceptions) from the Engineered Barrier System (EBS) following the containment period must not exceed one part in 100,000 per year of the inventory at 1,000 years following repository closure.
- The pre-waste-emplacement ground water travel time along "the fastest path of likely radionuclide travel" from the disturbed zone to the accessible environment must be at least 1,000 years. The boundary of the accessible environment was defined by the EPA regulations to be located five km from the boundary of the repository and covering no more than 100 km^2 in area.

These subsystem performance requirements drove the reposi~~tory sy~~stem design, e.g., selection of a waste canister design with an expected lifetime of 300-1,000 years. As previously noted, the natural features of the repository system (low and slow water flow; radionuclide holdup) were expected to be the dominant contributors to safety performance.

3.1.2 Principal SCP Repository Design and Natural System Features

The SCP repository design was based on emplacement of 70,000 MTHM of spent fuel and high-level waste in an array of vertical boreholes drilled into the floor of drifts in the Topopah Spring Member of the Paintbrush Tuff Formation. (The 70,000 MTHM limit was set in the NWPA and remains unchanged.) The areal power density for the repository was set at 57 kilowatts per acre, and the reference design was based on emplacement of 10-year-old spent fuel.

The SCP repository layout is shown in Figure 3-1 (DOE88a). Three main drifts traverse the length of the repository and the emplacement panels are accessed by side drifts from the mains. Entrance into the repository is through ramps located at the North end.

As previously noted, the site characterization database was quite sparse when the SCP was issued. It was expected that the water that could infiltrate the mountain and cause corrosion, waste form dissolution, and radionuclide release was "...limited to very small amounts" (DOE88). Based on annual precipitation of 15 centimeters, only about 0.1-0.5 millimeters/year were expected to percolate from the surface to the deep rock units where the repository would be located. Travel times to the boundary of the accessible environment were expected to be on the order of tens of thousands of years because flow through the unsaturated zone was expected to occur in the rock matrix.

Characterization of Yucca Mountain for the repository project began in 1978. It involved extensive drilling of boreholes and measurement of hydrologic properties such as hydraulic conductivity and transmissivity. Because of the complexity of the geohydrologic regime, the database at the time the SCP was issued was still characterized as "...scanty and incomplete." The basic model for the unsaturated zone was one of flow dominated by the partially saturated matrix. The saturated zone model was based on Darcian flow and a dual-porosity (fractures and matrix) concept.

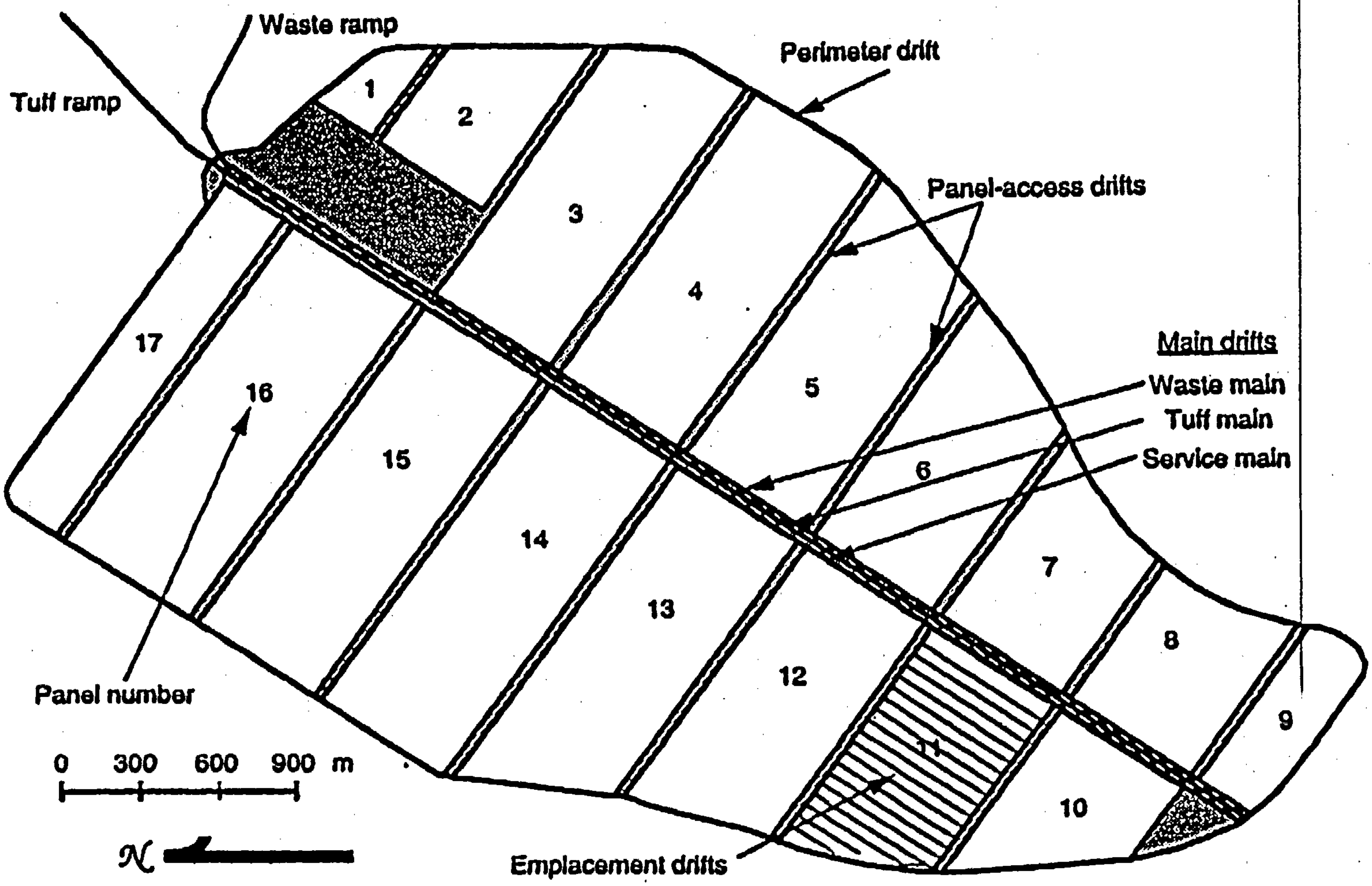

Figure 3-1. Layout of the Site Characterization Plan Repository

SuppApp- 630

The available models and data were used to estimate hydrologic parameters important to repository performance. The average annual precipitation was estimated to be about 150 mm/yr.

Because of the thickness and heterogeneity of the unsaturated zone above the repository horizon, temporal and spatial variations of infiltration were not expected to be the same at depth as at the surface.

Various estimates of the infiltration rate were made; all of them showed low rates. One estimate found that the infiltration rate at the repository horizon would be no more than 0.2 mm/yr, and the surface rate would be no more than 0.5 mm/yr. Another study estimated that the net infiltration rate would range from about 0.5 to no more than 4.5 mm/yr. Yet another study estimated the range at 0.015 to no more than 4.5 mm/yr. Modeling studies after the SCP was published generally used infiltration rates of 1.0 mm/yr or less. As discussed below, these types of values prevailed as a basis for unsaturated zone performance until the 1996-1997 time frame.

Because of the 10 CFR Part 60 subsystem performance requirements, estimates were made of ground water velocities and travel times. The SCP quotes findings by Sinnock et al. that the unsaturated zone travel time, for an infiltration rate of 0.5 mm/yr, would be a minimum of 9,345 years, a mean of 43,265 years, and a maximum of 80,095 years. If the infiltration rate was doubled to 1 mm/yr, the minimum travel time was decreased to 3,700 years, "...still greater than the amount of time required to satisfy the [regulations]." It was stated that "...the modeling effort has attempted to use the best available data, and it is believed the results obtained are realistic." As indicated by this statement, at the time the SCP was developed (and for a considerable period of time thereafter) the travel time through the UZ was believed to be sufficient to meet the 10,000-year requirement in the EPA standard.

Estimates of travel time in the saturated zone, which were based on Darcian flow and travel paths parallel to the hydraulic gradient and nearly horizontal, showed travel times of 30 years in the 3-km path in tuffacious beds of the Calico Hills Formation and 140 years in the 2-km path for the Topopah Springs Member, for a total of 170 years to the 5-km boundary of the accessible environment. It was noted that other factors such as dispersion, the existence of faults or impermeable zones, or vertical movement of water could affect the saturated zone travel times. It was also noted that "...at this time it is uncertain whether some or all of this mechanisms exist along the travel path." However, page 3-220 of the SCP states that more realistic data give an SZ travel time to the 5-km accessible environment boundary of 1,700 years (SCP88). In contrast, recent SZ travel time estimates presented to the NWTRB (EDD01) estimated travel times to a distance of 20 km downgradient to be between 640 years (median parameter values) to 900 years

(mean parameter values). A "refined conceptual approach," equivalent to the SCP estimate using more realistic data at that time, gave a travel time of 1300 years to the 20 km distance.

The SCP concluded that "...based on an upper-bound flux of 0.5 mm/yr, ground water travel time within the unsaturated zone from the proposed repository to the water table is estimated to range from about 9,000 to 80,000 yr," and "... the minimum ground water travel time from the edge of the repository to the accessible environment [5 km] under present conditions is approximately 9,200 years, well in excess of the 1,000 year limits required by 10 CFR Part 60.113(a)(2)."

With these expectations of high performance for the natural features of the repository system, the engineered barrier system could be the minimum required to meet regulatory requirements, as discussed below.

3.1.3 The SCP Engineered Barrier System

In accord with NRC's subsystem performance requirements, the waste package for the SCP design consisted of Type 304L stainless steel containers 4.76 m long and 0.66 m in diameter, with a wall thickness of 0.95 cm. Most of the commercial spent fuel was expected to be consolidated, but disposal of intact assemblies was planned for fuel assemblies with damaged rods. The HLW containers were similar to those for spent fuel but shorter.

The containers were to be backfilled with argon and welded shut. Fully loaded waste packages would weigh 2.7 to 6.4 metric tons, would have a power output of about 3.3 kW at the time of emplacement, and would have a surface gamma dose rate of about 50,000 rads per hour.

The waste packages were to be emplaced in 76-cm diameter holes bored into the floor of drifts in the underground workings. The boreholes were to be metal-lined and had a metal support plate at the bottom on which the waste package rested. A metal plug would be placed on the top of the emplaced package, the upper portion of the borehole would be filled with crushed tuff, and a metal cover would be placed on the floor of the drift. Eventually, the drifts would be backfilled with crushed tuff.

An important concept included in the SCP design was use of heat emitted by the waste packages to drive water in the rocks away from the emplacement cavities, thereby effectively drying out the repository host rock. The concept was seen to make a good repository setting (the unsaturated zone in a semi-arid environment), even better by delaying the eventual contact of water with the waste containers. The technical difficulties in characterizing performance under high thermal

load conditions were recognized in the SCP and was preserved as a significant technical issue in commentary, in 1999, on the Total System Performance Assessment for the Viability Assessment from external parties such as the TSPA Peer Review Panel (PRP99). This uncertainty played a significant role in DOE's decision to adopt the highly engineered EDA II repository design (described in Section 3.4 of this document).

The engineered barrier system (EBS) design, including the waste package design, was intended to comply with the subsystem performance requirements of 10 CFR Part 60, including ability for retrieval after 50 years. The package was intended to provide substantially complete containment of waste for a period of not less than 300 years, but no more than 1,000 years would be required. Thereafter the package was to limit the rate of radionuclide release from the EBS as required by the NRC subsystem performance objectives. With the anticipated high performance of the natural system barriers, the relatively modest performance expectation for the engineered barrier system was expected to be sufficient to meet the assumed (from 40 CFR Part 191) standard for cumulative releases.

The evolution of performance assessments, and the associated changing repository design, are described in the following sections, along with the progressively improved understanding of the natural barrier characteristics.

3.2 Design Options in the Total System Performance Assessments of 1991, 1993, and 1995

As previously noted, the TSPA evaluations reported in 1991, 1993, and 1995 were intended to guide site characterization activities and priorities, and to explore the effect of design alternatives on repository system performance. DOE carefully noted that none of the design concepts was intended to represent an actual repository design, and none of the results were intended to be a test of compliance with regulatory standards. However, to have a basis for assessing study results, outputs of the evaluations were compared to the total system performance standards in Subpart B of EPA's 40 CFR Part 191 regulations that had been adopted by NRC's 10 CFR Part 60 regulations.

Throughout this period, results of the site characterization work and other data acquisition programs were, as they became available, incorporated into the studies and used to improve the performance assessment models. Because the EPA Part 191 regulations set limits on radionuclide releases to the accessible environment boundary at 5 km, the site characterization work was focused on and near the repository footprint. The surface-based data acquisition program included activities such as drilling numerous boreholes, geologic mapping of trenches,

characterization of surface expression of faults, and daily acquisition of meteorological data. Excavation of the Exploratory Studies Facility (ESF), primarily during 1995 and 1996, enabled data acquisition activities at the repository horizon to proceed in accord with excavation progress and in parallel with the surface-based studies.

Highlights of the 1991, 1993, and 1995 TSPA analyses are presented below with focus on design options considered. As can be seen, the options considered ranged from the simple waste canisters in the SCP reference design to precursors of the VA design and the current design, EDA II. During the time period through 1995, clear evidence of limitations on the performance of the natural features of the repository was not yet available; the shift of emphasis to large, highly-robust packages was driven by logistics considerations (far fewer packages to handle), the decision to excavate the repository using a tunnel boring machine, and growing indications that very conservative assumptions and analyses would be expected by the licensing authority during licensing reviews.

3.2.1 TSPA-1991

The TSPA-1991 studies were the initial attempt to demonstrate TSPA concepts and methodology. The design concept for TSPA-1991 was that of the SCP: PWR fuel with an average burnup of 33,000 MWd/MTHM and BWR fuel with an average burnup of 27,500 MWd/MTHM would be consolidated into vertically emplaced stainless steel waste packages. The waste package performance evaluations were based on several assumptions not supported by detailed modeling studies. The waste package was expected to be initially dry due to heating produced by radioactive decay; this dry period would last from 300 to 1,300 years. After wetting, the container was expected to have a lifetime range of 9,500 years "to reflect the great uncertainty in container performance" (BER92). A total of 33,300 containers was included in the repository design.

3.2.2 TSPA-1993

Two separate but parallel performance assessments were conducted in 1993 - one by the DOE M&O Contractor (DOE94) and one by Sandia National Laboratories (WIL94). These parallel assessments are designated as the "M&O Approach" and the "SNL Approach" in the following discussion. The EBS designs used in these assessments resemble the design used in the TSPA-VA and the newer EDA II design, and represent the first attempt to examine designs that were developed to reflect anticipated repository conditions at Yucca Mountain.

3.2.2.1 M&O Version of TSPA-93

The M&O's TSPA-93 studies considered three areal power loadings -- 28.5, 57 and 114 kilowatt per acre. Waste packages using a thick, outer corrosion allowance material (CAM) and a thinner, corrosion resistant material (CRM) as the inner package wall were horizontally emplaced in drifts in the Topopah Spring Member of the Paintbrush Formation. The commercial reactor spent fuel loading was 63,000 MTHM contained in thirty-year old fuel with an average burnup of 36,437 MWd/MTHM (DOE94, p. 2-3). In addition, 7,000 MTHM in HLW from the defense programs was included. The commercial spent fuel was contained in 6,468 waste packages and the defense HLW was contained in 3,829 waste packages (DOE95, p. 8-15). (Note that this design concept reduced the number of waste packages required for commercial spent fuel by about a factor of 5 in comparison with the SCP design.)

The waste packages were comprised of an outer, mild steel corrosion allowance material and an inner, nickel-base corrosion resistant material, Alloy 825. Three thicknesses were considered for the outer layer: 10, 20, and 45 cm. The inner layer was either 0.95 or 3.5 cm thick. The packages were assumed to be placed horizontally on crushed tuff on the floor of the drifts.

The M&O TSPA-93 assumed an ambient percolation flux with an exponential distribution and an expected value of 0.5 mm/y. Two-thirds of the flux values were less than the expected value and one-third were greater. These low flux values reflected SCP expectations; results of site characterization studies had not yet had an impact.

Radionuclide sorption and decay were included in modeling of the unsaturated zone (UZ) but diffusion was not. Six layers were used to represent stratigraphy in the UZ below the repository. Nine vertical columns were modeled to represent UZ variability in thickness and stratigraphy over the repository area. Temperature profiles, Darcy fluxes, and liquid saturations, were developed for each stratigraphic layer for each thermal load as function of time. These determined dry out extent and duration in the near field. No far-field thermal perturbation was assumed.

Climate change was incorporated by assuming that the infiltration rate would vary from 1 to 5 times the base value with an average value of 2.5. Transition to a full glacial climate would occur linearly over 100,000 years then return to baseline over the next 100,000 years. This cycle was repeated over the one million year simulation time frame.

Retardation factors, developed for each nuclide for each stratigraphic unit, were similar to those used in TSPA-1991. Sorption and decay were included in saturated zone (SZ) modeling but not

diffusion. The SZ flux was assumed to have average value of 2 m/yr with a wide range from 4.7×10^{-6} m/yr to 390 m/yr. Only the longitudinal component of dispersion was considered in modeling of SZ radionuclide transport. A single porosity medium was assumed for the SZ.

3.2.2.2 SNL Version of TSPA-93

The SNL TSPA-93 studies considered both vertical (in borehole) and horizontal (in-drift) emplacement of waste packages and areal thermal loadings of 57 and 114 kilowatt per acre. Alternative waste package designs were also considered. Details are presented in Table 3-1 (WIL94).

Table 3-1. Repository Designs Evaluated by SNL in TSPA-1993

Emplacement Mode	Thermal Loading (kilowatt per acre)	Container Description	Waste Capacity (MTU/ container)	Heated Area (km^2)	Heated Area (acres)	Spacing (m)
Vertical In-borehole	57	Thin-wall, corrosion resistant high-Ni alloy	2	4.61	1,139	5.6
Vertical In-borehole	114	Thin-wall, corrosion resistant high-Ni alloy	2	3.14*	777*	2.8
Horizontal In-drift	57	Mild-steel CAM over thin-wall high-Ni CRM	8	4.63	1,144	23.2
Horizontal In-drift	114	Mild-steel CAM over thin-wall high-Ni CRM	8	2.33	575	11.6

* 2.33 km^2 (577 acres) for spent fuel and 0.81 km^2 (200 acres) for HLW.

The waste package for vertical, in-borehole emplacement was a thin-wall cylinder of a high-nickel alloy such as Alloy 825. The waste package had a outside diameter of 0.71 m, a wall thickness of 0.95 cm and a length of 4.76 m. The package could handle about 2 metric tons of spent fuel (e.g. 3 PWR and 4 BWR fuel assemblies) and weighed about 5 metric tons when loaded. The waste package for horizontal, in-drift emplacement was substantially larger with the ability to contain 21 PWR or 40 BWR fuel assemblies. The waste package was comprised of an Alloy 825 inner barrier 0.95 cm thick surrounded by an outer barrier of mild steel 10 cm thick. The two barriers were separated by a 0.6 cm gap. This waste package was 4.91 m long, had an outside diameter of 1.75 m and weighed more than 50 metric tons when loaded with spent fuel. This multiwall container was too massive to permit it to be tilted and moved for vertical emplacement and retrieval. Additional details on the two types of waste packages are summarized in Table 3-2.

Table 3-2. Spent Fuel Waste Package Inventory for TSPA-1993

Reactor Type	Amount of Waste (MTU)	Percentage of Total Spent Fuel	Weighted Average Age (Years)	Weighted Average Burnup (MWd/MTU)	Hybrid Waste Packages	Single Type Waste Packages
Borehole Emplacement*						
BWR	22,248	35.3	26.3	31,550	28,057	1,215
PWR	40,749	64.7	25.5	40,461		2,750
Totals	62,996	100	--	--	32,022	
In-Drift Emplacement						
BWR	22,183	35.3	26.4	31,533	--	3,109
PWR	40,646	64.7	25.5	40,433	--	4,531
Totals	62,829	100	--	--	--	7,640

* For vertical borehole emplacement, an additional 13,957 canisters would be required for vitrified HLW.

3.2.3 TSPA-1995

At the time TSPA-1995 was prepared, the regulatory framework was still in a state of flux. The National Academy of Sciences' Committee on Technical Bases for Yucca Mountain Standards issued its report in August 1995 (NAS95), but EPA had not promulgated the environmental regulations specific to Yucca Mountain. Given this situation, DOE chose in TSPA-95 to evaluate cumulative releases of radioactivity to the accessible environment based on cumulative normalized release limits included in Table 1 of 40 CFR Part 191 and maximum doses to individuals using ground water from a well in the tuff aquifer at the boundary of the accessible environment. In each case, the boundary of the accessible environment was assumed to be 5 km down the saturated zone hydraulic gradient from the edge of the repository (DOE95). Evaluations were also made against subsystem requirements in 10 CFR Part 60.

Repository design concepts investigated in TSPA-95 were based on 63,000 MTU of spent nuclear fuel and 7,000 MTU of defense HLW emplaced in horizontal waste packages (the same as TSPA-93). Two areal mass loading were considered – 25 MTU/acre and 83 MTU/acre. Both backfill and no-backfill options were analyzed as repository closure strategies. The use of backfill was expected to act as a capillary barrier to water and as a thermal management tool. Its use would increase waste package temperatures; evaluations of the temperature impacts of the backfill were included in the studies.

Commercial spent fuel was assumed to be 30 years old with a weighted average burnup of 36,666 Mwd/MTU. The same number of waste packages were assumed as in the TSPA-93 analyses performed by the M&O contractor (DOE95, p. 8-15).

"Low" (ca. 0.02 mm/y) and "high" (ca. 1.2 mm/y) infiltration rates were considered. These rates are in the range expected under the SCP; results of site characterization studies which showed that infiltration rates are actually in the range of 1-10 mm/yr, and currently average about 8 mm/yr, were not yet available for TSPA-95.

The waste package design concept for TSPA-95 was similar to that considered in TSPA-93; i.e., it consisted of a outer mild steel corrosion-allowance material (CAM) over an inner corrosion-resistant material (CAM) of Alloy 825. The waste container for either 21 PWR assemblies or 44 BWR assemblies was about 5.7 m long and about 1.8 m in diameter. The CAM thickness was 100 mm while the CRM thickness was 20 mm. A 21 PWR waste package would weigh about 66 tons and produce an average of 10 kW of heat at the time of emplacement. The waste package was assumed to rest on a gravel invert covering the bottom of a circular cross-section drift with a diameter of 5m.

In summary, the TSPA exercises and reports of 1991, 1993, and 1995 served several important purposes in the evolution of the Yucca Mountain repository design. In brief, TSPA-91 provided a baseline by introducing the TSPA concept and applying it to the SCP design. The subsequent TSPA-93 and TSPA-95 efforts explored the potential ranges of contributions of engineered and natural barriers to repository system performance. Key factors considered included the following:

- In the 1993-1995 time frame, DOE knew, as a result of enactment of the Energy Policy Act of 1992, that revised dose standards and requirements for demonstration of compliance would be forthcoming, so alternative dose standards and receptor locations were considered. Consequently, EBS designs more reflective of changing site characterization information were beginning to be assessed.

- As stated in TSPA-95, the SCP conceptual engineered design "... has been revised to take into account the possibility of alternative areal mass loads, as well as the decision to use a tunnel boring machine for the excavation of the emplacement drifts." In addition, the large multi-purpose canister design was adopted. These design considerations led to investigation of the performance characteristics of large, horizontally emplaced waste packages with alternative design details, such as the type and thickness of wall materials.

- Site characterization data were being incorporated into the TSPA-95 models and information base as they became available, but it was becoming increasingly apparent

that there was a high degree of inherent variability in natural system parameters, that performance of the natural barriers might not meet expectations expressed in the SCP, and that performance of the natural barriers might be difficult to demonstrate with confidence in licensing reviews.

- As a result of a limited database (limited in part by the fact that the high variability of natural features would require an extensive database for reliable characterization), potential bounds of the performance of the natural features were explored, using models not well founded. For example, TSPA-95 recognized that the principal contribution of the saturated zone to performance would be dilution, and the TSPA-95 developed and used models which predicted overall SZ dilution factors, for an infiltration rate of 1.25 mm/yr, of 4,500 at 5 km and 31,000 at 30 km. Subsequent expert elicitations confined the expected SZ dilution factor range to 1 - 100.

Collectively, these exploratory studies and their results laid the foundation for the Viability Assessment reference design and the TSPA-VA performance evaluations discussed below.

3.3 Design Features for the Viability Assessment - 1998

The Energy and Water Development Appropriations Act of 1997 specified that DOE prepare a viability assessment of the Yucca Mountain repository, thereby providing a status report on the project and identifying critical issues that must be addressed before the Secretary of Energy can make a recommendation concerning suitability of the Yucca Mountain site for disposal. The Viability Assessment report, which included a Total System Performance Assessment - Viability Assessment (TSPA-VA), was published in December 1998 (DOE98). Although the EPA standards had not been developed, DOE based its analyses on annual radiation doses to the individual members of the general public. DOE assumed a radiation dose limit of 25 mrem/yr. Releases from the ground water to the biosphere were evaluated at a point 20 km downgradient from the repository. Multiple exposure pathways were included in calculating doses to humans. Time histories to one million years were considered.

As previously noted, DOE considers that the TSPA-VA evaluations are the first that address a potential repository at the site. The major features of the repository design were similar to those in TSPA-95. However, in response to recommendations from the expert elicitation on waste package degradation, the waste package inner wall was Alloy 22 to provide enhanced corrosion resistance. The drifts were assumed to be concrete lined. Backfill was not included in the reference design but was examined as a design option. Use of ceramic coatings and drip shields were also briefly investigated as options.

The areal mass loading in the reference design was 85 MTU per acre with an initial heat output of about 100 kilowatt per acre. This is based only on 63,000 MTU of commercial spent fuel which will be emplaced in about 7,650 waste packages (DOE98, p. 3-30). According to the Draft Environmental Impact Statement (DEIS) (DOE99), the 7,000 MTU of DOE spent fuel and HLW waste also to be emplaced in the repository will require a total of about 22,000 waste packages.

UZ flow modeling for the TSPA-VA included climate, infiltration, mountain-scale flow and seepage into emplacement drifts. Climates modeled included the present day dry climate with an average annual rainfall of 170 mm/y, a long-term average climate with a rainfall of 300 mm/y and a superpluvial climate with an average rainfall of 450 mm/y. About 90 percent of the one million-year modeling period is spent under long-term average climate conditions.

The net infiltration rate in the TSPA-VA was assumed to be about 8 mm/yr (DOE98, p. 3-10) for the current dry climate. This value is substantially higher than the value of about 1 mm/yr used in TSPA-93 and TSPA-95, and it reflects the results of site characterization studies. The increased flow includes rapid travel through fast-path fractures which was not apparent from the earlier equivalent continuum models where fracture and matrix flows were closely coupled. The TSPA-VA used a dual permeability model to represent the full range of possible fracture-matrix coupling possibilities. Specifically, UZ transport was modeled using a three-dimensional, dual permeability finite element code (FEHM).

As noted above, Alloy 825 in the TSPA-95 was replaced with Alloy 22 (a highly corrosion-resistant nickel alloy) for the CRM in the VA waste packages. The drifts were lined with concrete. The waste packages were placed on carbon steel supports which in turn rest on a concrete invert to create level floors in the drifts. A typical 21 PWR waste package was 4.89 m long (without lifting extensions) and 1.65 m in diameter. The inner barrier of Alloy 22 was 2 cm thick while the outer barrier of A516 carbon steel was 10 cm thick (DOE98a).

The TSPA -VA was the first performance assessment in which the importance of fuel element cladding as a long-term barrier to radionuclide release was considered.

The TSPA-VA base case assumed that one waste package would fail by some unspecified juvenile failure mechanism at 1,000 years after repository closure (DOE98a). The probabilistic base case assumed 0 to 10 waste package failures at 1,000 years based on a log-uniform distribution.

The base-case expected-value TSPA-VA evaluations projected dose rates to the average individual withdrawing water from a well 20 km downgradient from the repository (based on conservative scenarios and modeling) as follows (DOE98, Figure 4-12):

- 0.04 mrem/yr at 10,000 years
- 5 mrem/yr at 100,000 years
- 50 mrem/yr at one million years

Results of more elaborate probability-weighted dose assessments (DOE98, Figure 4-26) show mean and median values for the peak dose at 10,000 years of 0.1 and 0.002 mrem/yr, respectively. Hence, all applicable dose values were found to be well below the proposed 15 mrem/yr individual protection limit. As discussed in Section 4, these results were developed using highly conservative, and in some cases unrealistically conservative, assumptions concerning performance factors and models for framing the performance scenarios analyzed.

The analyses found that the most important radionuclides contributing to individual dose for the first 10,000 years are Tc-99 and I-129; for the first 100,000 years they are Tc-99 and Np-237, and for one million years they are Np-237 and Pu-242.

The most important factors contributing to uncertainty in the peak dose rate over the first 10,000 years (in decreasing order of importance) were determined to be the fraction of waste packages contacted by seepage water, the mean corrosion rate of the waste package Alloy 22 inner barrier (a contributing uncertainty is the effect on corrosion rates of carbonate dominated ground waters resulting from contact with the drift lining), the number of juvenile waste package failures, and the saturated zone dilution factor (DOE98, Figure 4-34). These uncertainties were to be addressed by the design alternatives examined and selected for the new repository design (EDA II) as described below.

The TSPA-VA assessment results showed that calculated doses within 10,000 years were dominated by very conservative release assumptions. These assumptions, in turn, were associated with arbitrary and non-mechanistic assumed juvenile failures of the waste packages. As a consequence, subsequent attention focused on improved approaches for evaluating such juvenile failures.

3.4 Enhanced Design Alternatives - 1999

As stated in the VA documentation, the design concept used for the VA and the TSPA-VA evaluations was intended to be a step in design evolution to the design that will eventually be used

for the license application. Even though the site characterization data indicating infiltration rates that were much higher than previously expected were available for the VA, other data (e.g., concerning corrosion of waste package materials) were still limited, and the VA made extensive use of the results of seven expert elicitations that had been conducted during 1996 and 1997.

Subsequent to publication of the VA, DOE began to develop an improved repository design. The basis for the design development effort was a group of Enhanced Design Alternatives (EDA). Six EDA designs were evaluated and the EDA II design (described below) was recommended by the M&O contractor to DOE as the preferred approach. This recommendation was accepted by DOE management in September 1999. Design features for the EDA II design are discussed in Section 3.4.2.

In parallel with DOE's EDA design development effort, substantive action to revise the regulatory framework was occurring for the first time since the original NRC and EPA regulations for Yucca Mountain were promulgated in the 1980's. On February 22, 1999, the NRC published their proposed 10 CFR Part 63 regulations which set a dose limit of 25 mrem/yr and eliminated the subsystem performance objectives included in 10 CFR Part 60. In August 1999, EPA issued for comment the proposed 40 CFR Part 197 environmental radiation protection standards for Yucca Mountain (EPA99). These standards would require DOE to demonstrate a reasonable expectation for 10,000 years after disposal that the annual committed effective dose equivalent to the reasonably maximally exposed individual is no more than 15 mrem (CEDE). The draft standard also imposed ground water protection requirements. The EPA's proposed rule had not been published at the time the EDAs were being evaluated, but the individual dose standard is the same as that incorporated in the generic standard (40 CFR Part 191) and used in the WIPP certification process.

3.4.1 Basis for the Current Design

Reviews of the repository design concept and performance assessment results for the Viability Assessment by parties such as the Nuclear Waste Technical Review Board, the NRC, and the Performance Assessment Peer Review Panel determined that some of the engineered features of the VA repository contributed significantly to uncertainty in the Total System Performance Assessment (TSPA) results. Major design factors contributing to performance uncertainty included:

- The high areal mass (thermal) loading, 85 MTU/acre, and resulting high temperatures in the rocks surrounding the repository caused significant uncertainties concerning thermal, hydrological, chemical, and mechanical coupling effects. It also caused

uncertainties concerning the behavior of rock structure and ground water surrounding the drifts during repository temperature variations with time.

- The use of concrete lining in the drifts caused concerns about the effect of materials in the concrete on the chemical constituents in ground water that contacts waste packages and the effect of those constituents on the corrosiveness of the water.

- The use of carbon steel as the Corrosion Allowance Material and the outer wall of the waste packages, and use of Alloy 22 as the Corrosion Resistant Material and the inner wall of the waste packages, caused concern that the carbon steel could create potential for crevice corrosion of the Alloy 22, thereby increasing the rate of penetration of the Alloy 22 by about a factor of 25 and consequently greatly reducing the waste package lifetime.

- The waste packages were not protected from the potential that ground water at the repository horizon could, at times relatively soon after emplacement, drip onto the packages and thereby produce aqueous corrosion, enter the package interior, contact the waste form, leach out radionuclides, and transport the radionuclides to the environment.

The DOE's development and selection of an improved repository design was directed at being responsive to these concerns.

3.4.2 Selection of the Repository Design for the Site Recommendation

DOE used the License Application Design Selection (LADS) process to select the engineered design for the Site Recommendation. Six Enhanced Design Alternatives (EDA) were defined and comparatively evaluated. They were identified as EDA options I, II, IIIa, IIIb, IV, and V. Options IIIa and IIIb differed in the choice of waste package materials but were otherwise the same.

In defining the EDA options, specific design features were used to address the important performance uncertainties. All EDA options use a drip shield of corrosion-resistant material to divert water from the waste packages and to control the waste package environment; all EDA options also use a corrosion-resistant material as the outer wall of the waste package and limit the use of cementitious material in the repository. The options differ in their use of high or low thermal loading, emplacement configurations and waste package energy densities, and backfill.

Use of evaluation criteria and a comparison methodology produced the results of analyses of the EDA options shown in Table 3-3. These results produced a recommendation by the DOE's

Table 3-3. Principal Results of EDA Analysis
(Source: K.J. Coppersmith, TRB99a)

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

SuppApp- 644

Management & Operations contractor that the EDA II option be selected for the Site Recommendation (SR). DOE endorsed the contractor's recommendation in September 1999, and this design is now being used as the basis for development of the SR.

3.4.3 Comparison of the EDA II and Viability Assessment Designs

The principal EDA II and VA engineered design features are compared in Table 3-4. DOE estimated that the net present value for development, construction, operation, and closure of the VA repository would be about $10.1 billion; the estimated net present value for the EDA II repository is about $11.0 billion (Table 3-3). The cost difference for the two designs is minimized by the assumption that the drip shields and backfill for the EDA II design would be installed at the time of repository closure, i.e., 50 years or more after the end of emplacement operations.

Table 3-4. EDA II/VA Design Comparison (Source: M.C. Tynan, TRB99a)

Design Characteristics	EDA II	Viability Assessment Design
Areal Mass Loading	60 MTU/acre	85 MTU/acre
Drift Spacing	81 m	28 m
Drift Diameter	5.5m	5.5 m
Total Length of Emplacement Drifts	54 km	107 km
Ground Support	Steel	Concrete lining
Invert	Steel with sand or gravel ballast	Concrete
Number of Waste Packages	10,039	10,500
Waste Package Material	2 cm Alloy 22 over 5 cm stainless steel 316L	10 cm carbon steel over 2 cm Alloy 22
Maximum Waste Package Capacity	21 PWR assemblies	21 PWR assemblies
Peak Waste Package Power (blending)	20 percent above average PWR waste package power	95 percent 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 EDA II and VA designs are compared qualitatively with respect to the performance uncertainties discussed in Section 3.4.1 in Table 3-5. As shown in this table, the EDA II design, in comparison with the VA design, has a significantly reduced areal mass loading, no concrete liner, a waste package design which has the corrosion resistant material on the outside rather than on the inside, and use of drip shields and backfill to help reduce and defer contact of water with the waste packages. Each of these design features is responsive to concerns for performance

Table 3-5. Impact of EDA II Design Features on Performance Uncertainties

Design Feature	VA Repository	EDA II Repository	EDA II Impact
Areal Mass Loading	85 MTU/acre	60 MTU/acre	Reduce thermal coupling issues
Drift Spacing	28 meters	81 meters	No temperature rise above boiling point in rock between drifts; reduces overall performance uncertainty
Drift Liner and Invert Material	Concrete	Steel	Eliminate effect of concrete constituents on water chemistry; reduce corrosion rates and radionuclide release rates; increases package lifetime
Waste Package Materials	10 cm carbon steel over 2 cm Alloy 22	2 cm Alloy 22 over 5 cm 316L stainless	Eliminate crevice corrosion potential; reduce Alloy 22 corrosion rate by factor of 25 or more; increases package life
Peak Waste Package Power	95 percent above average	20 percent above average by blending assemblies	Reduce thermal gradients; less driving force for water movement and degradation processes
Drip Shield	None	2 cm Titanium 7	Protect waste packages; defer contact by water and eliminate juvenile failure potential
Backfill	None	Yes	Divert water from waste packages; protect against rockfall

uncertainties in the VA design; each helps to mitigate performance uncertainties and to improve expected repository system performance with respect to timing and quantities of radionuclide release. Improvement is obtained either by delaying penetration of the waste package walls or by changing the expected physical/chemical conditions to reduce the amount of radionuclides that could be transported out of the EBS by migrating ground water that moves through the repository.

3.5 Evolution of the Comparative Contributions of Engineered and Natural Barriers to Repository System Performance

As previously noted, the evolution of repository design and performance has been characterized by greatly augmented contribution of engineered barriers to performance and greatly diminished contributions of the natural barriers. The natural barriers of principal significance are the rate of infiltration of water into the mountain; the water percolation flux at the repository horizon; the rate of seepage of water into the drifts and onto the waste packages; travel times in the unsaturated and saturated zones; radionuclide holdup on rock formations as a result of sorption; and dilution of radionuclide concentrations as a result of dispersion and mixing of contaminated

and uncontaminated water. Acquisition of data to characterize these performance factors has been underway since inception of the Yucca Mountain project, is continuing today, and will continue through the post-emplacement performance confirmation period if a repository is built at the site.

The diminished role of natural barriers in repository performance expectations occurred relatively abruptly in the 1996-1997 time frame, and was first made evident in the TSPA-VA evaluations (which, as previously noted, were the first TSPA evaluations for a potential "actual" repository at the site). In comparison with the prior TSPA studies, the TSPA-VA evaluations used greatly increased infiltration values and greatly reduced dilution factors for the saturated zone. For example, the SCP and all TSPA studies prior to the TSPA-VA assumed infiltration rates on the order of one mm/yr or less; in contrast, the TSPA-VA used a current-climate average infiltration rate of 7.7 mm/yr and a long-term climate average infiltration rate of 42 mm/yr. Models and analyses in TSPA-95 projected overall dilution factors for the saturated zone on the order of 1,000 to 100,000; TSPA-VA used a dilution factor range of 1-100 with a median value of 10.

These changes were brought about principally by the following:

- In 1996, Flint et al. (FLI96) reported analysis of accumulated site characterization data which demonstrated that the infiltration rate is on the order of 1-10 mm/yr and is highly variable over the area of the repository footprint.

- In 1997, D'Agnese et al. reported a regional scale model of the Death Valley hydrologic regime in Nevada and California (DAG97).

- In 1997, an Expert Elicitation on unsaturated zone flow was conducted; based on available data, the experts estimated the mean infiltration rates to range from 3.9 mm/yr to 12.7 mm/yr (DOE97).

- Data showing that Cl-36 from nuclear weapon tests had traveled to the repository horizon in 50 years or less were interpreted to show that there are fast paths for flow through the unsaturated zone, the infiltration rate had to be at least about 2 mm/yr, and the fast flow apparently took place in the fracture zones (Fab98).

- An improved model for flow and transport in the unsaturated zone, based on integration of hydrologic, mineralogic, structural, hydrochemical and geochemical site characterization data, was reported and made available in 1997 for the TSPA-VA (BOD97).

- An Expert Elicitation on flow and radionuclide transport in the saturated zone was conducted (GEO98). The experts rejected the models used in TSPA-95 which showed very large dilution factors, and they emphasized the limitations of processes that would cause dilution of contaminant concentrations. The experts also took note of the extreme lack of data to characterize the geohydrologic regime in the saturated zone

beyond the 5-km boundary of the accessible environment (the result of prior focus on the requirements of the EPA's 40 CFR Part 191 regulations). The experts expressed their belief that radionuclide transport would be by movement in vertically thin plumes through flow tubes beneath the repository; they also recommended that the overall dilution factor be constrained to the range of 1 to 100, with a median value of 10.

The results of these activities and findings were incorporated into the basis for the models and performance parameter values used in the TSPA-VA. For example, the Expert Elicitation recommendations concerning dilution in the saturated zone were adopted directly, and a new one-dimensional stream tube model for radionuclide transport in the saturated zone was developed in response to the experts' opinions concerning flow in the saturated zone.

Overall, the models and assumptions adopted for the TSPA-VA analyses resulted in essentially no contribution to performance from transit and holdup in the unsaturated zone, and dilution of radionuclide concentrations during transit of the saturated zone to a location 20 km from the repository occurred by only a factor of 10 in the base case. Dilution during pumping by the dose receptor was assumed not to occur.

Despite minimization of the role of natural barriers in the TSPA-VA analyses, the TSPA Peer Review Panel (PRP99) stated, "The current treatment of saturated zone (SZ) flow and transport at Yucca Mountain is far from satisfactory." The Panel noted three main areas of weakness in the TSPA-VA treatment:

- The lack of data for some important parameters,
- The incomplete nature of site characterization, and
- Continuing questions regarding the adequacy of the numerical models.

The basic remedy for these weaknesses, which could permit increased and justified reliance on performance of the natural barriers, is to significantly expand the database of site characteristics and, by so doing, increase understanding of the functioning of the natural barrier. To do so would, however, be costly and time-consuming, and may not be necessary given the extreme reliance on engineered barriers that has been developed to reduce the importance of uncertainties in natural barrier performance (see the description of the current repository design in Section 3.4.2). Indeed, in 1996 the Nuclear Waste Technical Review Board noted that "...there are no data to support a realistic estimate of dilution...[and it is not clear] whether further characterization can provide the data for reducing the uncertainty...further studies of the saturated zone beyond those now planned or under way...may not be cost-effective" (TRB96). These considerations indicate that the DOE's move to a more highly-engineered repository design was directed by a realization of the limitations of further characterization efforts on the complex flow system in and around the site,

and the recommendations of external parties to move in the direction of enhanced design to lower the uncertainties.

At present, Nye County, in cooperation with DOE, is conducting a drilling and testing program using boreholes drilled approximately along a radius 20 km from the proposed repository location. These data will expand knowledge of the characteristics of the saturated zone in the valley-fill alluvium. Data available to date indicate that the geologic formations are highly complex, and that flow may occur principally in channels within the alluvium (NYE00). The results of these and other tests planned by DOE may serve only to confirm that significant contributions to performance from features of the saturated zone are not to be expected.

In contrast to the situation for the saturated zone, ongoing experiments in the unsaturated zone at the repository horizon may provide a basis for increased reliance on, or confidence in, performance of natural features in the unsaturated zone in future TSPA evaluations. Experiments concerning seepage into drifts (which has been consistently shown by TSPA evaluations to be one of the most important performance parameters) are showing that seepage is highly limited, and no natural seepage into drifts excavated to date has yet occurred. A world-wide investigation of natural analogs has also shown that seepage dripping into underground openings like those that would be characteristic of the repository is highly limited or non-existent because of capillary forces (TRB00a). The most recent report on the seepage work (TRB00b) indicated that the current seepage model matches the limited available data reasonably well, and that the model predicts a seepage threshold of 200 mm/yr for the rock formations at the repository horizon.

Seepage was incorporated into TSPA modeling for the first time in the TSPA-VA. The TSPA Peer Review Panel found the modeling approach to be "...both novel and informative" (PRP99). The modeling approach assumed steady-state flow in a fracture continuum, in which seepage starts where conditions exist for the drift surface to become fully saturated. The percolation flux threshold was estimated to be in the range 2-3 mm/yr, i.e., approximately the same as the current infiltration rate.

As noted above, experiments to date are indicating that the seepage threshold is actually on the order of 200 mm/yr. (This value corresponds to the high end of the values used in the TSPA-VA for the superpluvial glacial period in the VA climate model.) Available data are, however, limited, and the threshold will be highly sensitive to geometric and wetting conditions on the drift wall. In addition, seepage patterns and rates may change as a result of thermomechanical and thermochemical effects, and rock fall as a result of seismic events. The Peer Review Panel recommended further testing, which is currently underway (TRB00b).

DOE has recently adopted a technique termed "neutralization analysis" to characterize the contribution of individual performance factors to overall repository system performance (TRW00). The technique is being applied to the EDA II design; its use, and the relative roles of the engineered and natural barriers for the EDA II design, are discussed in Section 4.6. In general, the natural barriers play even less of a role in the current EDA II repository design than in the VA design because of further augmentation of engineered barriers in the EDA II design.

3.6 Summary of Factors Affecting Evolution of the Repository Design

As described above, the evolution of the design of the Yucca Mountain repository and its engineered barrier system has been an iterative process occurring, to date, over an eleven-year period from 1988, when the SCP was issued, until 1999, when the EDA II design was selected to be the basis for the Site Recommendation scheduled to be made in 2001. The evolutionary process has been driven principally by the following factors:

- Findings, from site characterization data, that performance of the natural barrier system will be significantly less than was expected when the SCP was issued. Specifically, infiltration rates are much higher than had been expected, water travel times in the UZ are faster than had been expected, and dilution of radionuclide concentrations will be much less than had been modeled as recently as 1995.

- Findings, from TSPA evaluations of design options and natural barrier performance models, that the SCP engineered barrier design concepts resulted in a high degree of uncertainty of ability to achieve compliance with EPA's 40 CFR Part 191 total system release standards and NRC's 10 CFR Part 60 subsystem performance requirements.

- As a result of DOE/NRC Technical Exchanges, development of NRC's Issue Resolution Status Reports, and external reviews, development of understanding of the rigor, depth, and limits on uncertainty that must be addressed in order to prepare a safety case adequate for licensing reviews.

- Results of external reviews such as those by the NWTRB, the TSPA Review Panel, and NRC staff, and understanding of the sources and magnitudes of uncertainties and technical issues in data, performance models, and performance assumptions that are significant to the adequacy and defensibility of the safety case.

In summary, the engineered design of the repository has evolved as a result of progress along a learning curve involving understanding of what the engineered and natural barriers can and cannot do in the Yucca Mountain setting, understanding of the essential elements of a safety case that is adequate for licensing reviews, and understanding of the needs for design approaches and data to bring uncertainties to acceptable levels. Identification of "acceptable levels" of uncertainties is related to EPA's concept of "reasonable expectation" and NRC's concept of "reasonable assurance", discussed in Section 5. The EPA standards have included, since promulgation of 40 CFR Part 191 in 1985, and through revised Part 191 in 1993, Part 194, and proposed Part 197, individual-protection standards of 15 mrem/yr CEDE (or equivalent), human-intrusion standards of 15 mrem/yr CEDE (or equivalent), and ground water protection standards derived from the Safe Drinking Water Act.

It is noteworthy that the design evolution has not been driven by EPA's 40 CFR Part 191 standards concerning radionuclide releases or by anticipated EPA dose standards. Examination of the DOE performance evaluations to date show that there are many alternative means to reduce uncertainties in performance projections, even with limited contributions of natural barriers to repository system performance. What is necessary is to build a solid foundation, through use of data, reasonable performance models, and reasonable assumptions, to demonstrate that the safety case is a reasonable and appropriate representation of expected repository performance.

3.7 EDA II Design and the TSPA-SR

As discussed in Section 3.6, DOE has evolved the repository design over a number of years from one emphasizing the natural barriers of the site to one with much greater reliance on engineered barriers. Among the reasons for this shift in emphasis was an increasing realization that collecting data to resolve residual uncertainties in the behavior of the natural system would be more costly than to develop and use engineered barriers that would eliminate the concern over those uncertainties. Following the Enhanced Design Alternatives program in 1999 (Section 3.4), the program focused on the EDA II design as the basis for the next iteration of the TSPA, known at the TSPA for Site Recommendation (TSPA-SR).

The TSPA-SR is intended as an update and improvement of the TSPA for Viability Assessment (TSPA-VA) (DOE98a), and as technical support for the Site Recommendation. Changes made to the TSPA models were intended to address criticisms of the TSPA-VA modeling approaches, to evaluate the system with more elaborate and soundly based modeling approaches. In addition, greater emphasis was placed on quantification of uncertainties that were not addressed in the TSPA-VA. In particular, in TSPA-SR greater emphasis was placed on the potential for igneous

disruption of the repository, on waste package degradation mechanisms potentially leading to early failures, and on potential human intrusion events. Considerably more attention was focused on evaluating the robustness of model assumptions and the influence of various engineered barriers than had been done previously.

The TSPA-SR supports the mandated site recommendation process in Sections 112 and 114 of the Nuclear Waste Policy Act (NWP83, NWP87). The site recommendation is an advanced stage of development of a recommendation by the Secretary of Energy to the President regarding the suitability of the proposed site for development. Since it is an integral part of the legal process for determination of the suitability of the repository to proceed toward a key decision step, the intent is for the TSPA-SR to be a strongly defensible analysis, and to form the foundation for the TSPA to be used in a license application.

3.7.1 New Approaches in the TSPA-SR

The primary scenarios evaluated in TSPA-SR are: (1) a nominal scenario, (2) an igneous scenario, and (3) a human intrusion scenario. In addition, assessments were conducted that evaluate the robustness of the analysis to extreme assumptions regarding system behavior, such as very early failure of engineered barriers. These assessments were conducted as part of a series of analyses intended to investigate "barrier neutralization," "uncertainty importance," sensitivity, and robustness of the TSPA. As such, they are regarded as parallel and supporting lines of argument in the Repository Safety Strategy, but are not central to TSPA-SR conclusions regarding regulatory compliance.

3.7.1.1 The Nominal Scenario

The "nominal scenario" is intended to represent the "sequence of anticipated conditions" (TRW00a). This is contrasted with "discrete, unanticipated events that disrupt the nominal case system" (TRW00a). That is, the sequence of external events and processes influencing the system in the nominal scenario represent only gradual degradation processes, with discrete, rapid degradation processes characterized as "disruptive events." The intent of the TSPA is both to show "how the system is thought to behave, but also to provide information on how much uncertainty is associated with each total system performance assessment component..." (TRW00a). **To that end, the analyses in the nominal scenario are intentionally biased toward conservatism in assumptions and choices of parameters.** Consequently, despite using scenarios that represent "anticipated conditions," the expected values of the consequences of the nominal scenario should not be interpreted as the expected consequences of the repository. Instead, the

"expected values" are a mathematical expression of a conservative representation of reality. This approach is generally acknowledged to be an appropriate approach to developing defensible TSPA analyses for repositories. Nevertheless, while a conservative approach to defining performance scenarios is typically used in TSPAs, proper interpretation of the results and subsequent decision making must be done with an understanding of the nature and extent of the conservatism embedded in the TSPA results. These points are key to understanding the TSPA-SR results in the context of reasonable expectation (described in Section 5) of compliance.

There appears to be consensus among DOE and EPRI commentators that the assumptions in the nominal case of the TSPA-SR are defensible and conservative, and in some cases very conservative. EPRI (EPR00) provided a long list of "departures from reality" in assumptions in the TSPA-SR. Essentially all potentially non-conservative assumptions listed were offset by an associated conservative assumption. However, there were numerous conservative assumptions that were not offset by any balancing approach. Among the most important conservative assumptions in the TSPA-SR are (EPR00):

- The model for hydrogen absorption on the titanium drip shield can be considered very conservative since it assumes that all the hydrogen absorbed during general corrosion will remain in the residual wall thickness and is available to induce hydrogen-induced cracking (HIC). This constitutes a very conservative assumption for the materials in the EDA II design. Without hydrogen absorption, dripshield lifetimes would be extended to greater than 30,000 years (EPR00). The primary effect of modifying this assumption would be to displace the dose curve out further in time, lowering doses calculated in the first 100,000 years by perhaps two orders of magnitude.

- The model for crevice propagation, if it were to initiate, is conservative. The crevice propagation is assumed to progress in a conservative non-mechanistic manner that may allow moisture ingress into the waste package. However, EPRI (EPR00), in comparing the potential effects of crevice corrosion on the failure time of the waste packages, found that it had only moderate effects (about 1,000-2,000 years) on the failure time.

- The initiation of stress corrosion cracking in the annealed final closure weld is a conservative assumption. EPRI argued that the material properties and the stress-state the waste package will experience imply that the probability of initiation of stress corrosion cracking is negligible, approaching zero. Eliminating this mechanism from the model may delay the onset of releases for several ten of thousands of years (EPR00, Figure 5-17).

- The cladding is assumed to be in an extremely aggressive environment, representing severe conditions for corrosion (DOE01). It is assumed that fluoride enters the waste package and comes in contact with only the cladding. The model does not account for buffering the fluoride by the basket internals. Accounting for this buffering would tend to provide a competitive mechanism for reaction of the fluoride, in turn providing a

much less aggressive environment for the cladding. In addition, for fluoride to enter the waste package, significant water would need to flow through the crack, diluting the concentration of the fluoride and lessening the impact. It is unclear whether these concentrations might be decreased enough to eliminate fluoride corrosion initiation entirely. If fluoride effects are eliminated, one would expect the onset of releases to be significantly delayed, since the reaction of cladding with fluoride is the primary initiation reaction in the DOE model. The TSPA-SR also assumes that the fluoride contacts the cladding in a limited area, which is argued by EPRI (EPR00) to be extremely conservative. In presenting an alternative model for cladding corrosion, in which corrosion was treated as general in nature (not specifically driven by contact with fluoride), EPRI calculated the median time to cladding failure as between 25,000 and 70,000 years, for dripping and dry conditions, respectively. This result contrasts with the barrier sensitivity analysis presented by DOE (DOE01, Figure 4-214), which shows little difference between the base case analysis and one in which virtually no credit is given for cladding corrosion.

In addition, it is noted that the flow model at the repository level includes an assumption that seepage initiates when a percolation threshold of 10 mm/yr is reached. Research on this effect suggests that a threshold value of 200 mm/yr is needed to overcome capillary effects (TRB00b). Notably, the only extant measurements associated with the threshold value indicate 200 mm/yr in the middle nonlithophysal unit of the Topopah Spring Tuff (DOE01, p. 4-92). This value is treated as an extreme end of a probability distribution in the TSPA-SR. Consequently, this assumption represents a significant level of conservatism, and particularly overestimates the effects of wet-climate states. Applying a higher threshold value would imply that the emplacement drifts would experience dry conditions for a considerably longer time.

A key change to the TSPA-SR compared with the earlier TSPA-VA was the treatment of manufacturing defects in the waste package. In the TSPA-VA, DOE assumed that some defects would lead to almost instantaneous releases from the repository. These early failures dominated the dose consequences in the period less than 10,000 years. However, these assumed early failures were somewhat arbitrary and not based on any known mechanism. For the TSPA-SR, the initiation of early failures was evaluated based on established engineering approaches for evaluating the likelihood of manufacturing defects, which are subsequently not identified during inspections. This approach, which is far more reasonable than the TSPA-VA approach, is nonetheless coupled with conservative models and parameters for corrosion initiation and propagation. The resulting approach, while still conservative, has shown the early failures used in the TSPA-VA to be non-mechanistic and implausible (DOE01).

Despite the apparent level of conservatism of the nominal scenario, there are no significant doses to the RMEI in the time period over which the performance objectives apply. The conservatism of

the nominal scenario leads to releases and subsequent doses to the RMEI during the period 10,000 to 100,000 years. Less conservative assumptions could well delay the releases until after 100,000 years.

3.7.1.2 Igneous Scenarios

The igneous scenario is subdivided into two scenarios: eruption and intrusion. The eruption scenario refers to penetration of the repository, leading to total disruption of waste packages and drip shields encountered by the magma, bringing waste to the surface. Doses result from ash eruption, with downwind transport, redistribution of ash at the surface, and subsequent human exposures. The intrusion scenario refers to penetration of the repository by magma, leading to total disruption of waste packages and drip shields encountered by the magma, but without further movement of radionuclides. However, since the engineered barriers are assumed to be totally destroyed, this scenario functions as equivalent to assessing juvenile failures of waste packages. Releases for the magma intrusion scenarios are via releases to ground water from the disrupted waste packages.

DOE01 has described the process by which the probability of occurrence of the igneous scenarios was derived. A panel of ten experts representing a wide range of expertise was assembled to interpret the volcanic hazard. The panel evaluated existing data, tested alternative models and hypotheses, and produced an integrated assessment of the volcanic hazard. The use of this procedure may have elicited slightly overstated probability of occurrence. The panel was concerned that some past basaltic activity in the area may have been eroded or buried by younger sediments. Consequently, the panel formally recognized this possibility by including these undetected volcanos into their estimates of the number that have occurred. DOE00a stated that most common multiplier for hidden events was 1.1 to 1.2 of the known volcanic events, despite the fact that there is no known episode of magmatic intrusion in the Yucca Mountain region that has not been accompanied by a surface expression.

The mean estimated annual frequency of intersection of the repository by a dike is 1.6×10^{-8}. The 5th and 95th percentiles of the annual probability are 7.6×10^{-10} and 5.0×10^{-8}, respectively. Shifting even selected probability values by 10-20 percent is unlikely to reduce the mean annual probability below the scenario cutoff value of 10^{-8}. Furthermore, DOE00a cites a series of estimates for the probability of intersection of the proposed repository at Yucca Mountain published during 1982-1999. These values cluster between $1\text{-}3 \times 10^{-8}$, with a few values as high as 10^{-7} for very conservative assumptions, and other values as low as 10^{-10} for less conservative assumptions. Regardless, a series of investigators have suggested that a probability slightly above 10^{-8} is credible. Hence,

while the probability may be slightly overstated by the TSPA-SR analysis, it is unlikely that the igneous scenario can be eliminated solely by arguments related to the probability of occurrence.

By contrast, the consequence analysis conducted for the TSPA-SR appears to be very strongly biased toward conservatism. All eruptions are assumed to be violent strombolian for their entire duration. The justification for this assumption is that this is a conservative approach, and that it is consistent with the capabilities of an existing NRC computer code, ASHPLUME. EPRI (EPR00) strongly criticized this assumption, and concluded that strombolian eruptions are both rare in extensional environments like Yucca Mountain, and are not consistent with existing basaltic deposits associated with past events in the region. EPRI (EPR00) suggested that the Pu'u O'o eruption of Kilauea Volcano, Hawaii would be a better model for the type of eruption that may occur in the Yucca Mountain region. This type of eruption would have much less severe consequences than would a violent strombolian eruption. NRC (NRC99a) notes that such "...low-energy, low-dispersivity eruptions have limited potential to disperse HLW to critical group locations."

In the TSPA-SR it is assumed that the magma destroys all waste packages and drips shields that it contacts, making the full inventory of those packages available for transport. The justification for this assumption is that it is conservative, and that other assumptions would be difficult to support (TRW00a). The TSPA-SR is based on a very high temperature (1200 C) in the dike. It has been noted (EPR00) that literature information is available that would indicate that dikes of similar size to the drifts would solidify in 10 to 20 days, and that the expected contact temperature between the magma and the containers would be substantially (as much as 40%) lower than the value used by DOE. Taking these effects into account would drastically reduce release rates associated with this scenario, since the containers would likely survive intact at lower temperatures. EPRI (EPR00) also notes the existence of natural analogues for this effect, in which cars, telephone poles, and other objects in the magma path are embedded in the magma rather than consumed by it. In the supporting documentation for the TSPA-SR, DOE (DOE00) acknowledges these temperature effects, conduct modeling of the thermal interactions of waste packages and magma, and presents a conceptual model in which the waste packages are primarily intact after interactions with magma. This conceptual model was not used in the TSPA-SR.

These two assumptions (waste package destruction and type of eruption), if modified, have the potential by themselves to lead to minimal or zero releases from the waste packages in the case of igneous activity.

A number of additional assumptions in the TSPA-SR igneous models are also conservative (EPR00), but would tend to have less profound impacts on the results:

- Effects associated with magma viscosity and velocity are conservative. It is assumed that sufficient magma enters the emplacement drift to contact between 6 to 18 waste packages and move them around, contributing to waste package failure. Assumptions of less violent behavior would tend to decrease releases directly in proportion to the number of damaged containers.

- The assumed waste form particle size after disruption is conservative. When the waste form is exposed to the erupting magma it is assumed that the spent fuel is pulverized into very fine particles. The shearing forces involved in magma eruption are unlikely to be able to cause enough grinding of the ceramic fuel to pulverize the majority of the fuel into a fine powder. This is conservative for the eruption scenario because a fine powder is more easily dispersed over long distances. This assumption is inconsistent with the conceptual model of dike-waste package interactions presented by DOE00. In that report, waste packages were described as being substantially intact following interactions with a dike. If the waste is not pulverized during the eruption, the eruption scenario, which relies entirely on an airborne pathway, would likely be inconsequential.

- The fuel particles are assumed to be on or near the top of all of the magma and eruptive material as it falls back to earth. This assumption is conservative since the majority of the dose from the eruptive scenario is via the inhalation pathway. Waste buried deeper within the fallen ash is less likely to be resuspended by the wind. The particle size assumption discussed above would make this assumption even more conservative.

- The wind is conservatively assumed to always blow toward Amargosa Valley, thereby ensuring the ash fall lands on the greatest local population. The SCP Chapter 5 (DOE88a) shows that no more than about 15 percent of the surface winds are from the north, and at higher elevations winds are generally from the east or southeast. Consequently, this assumption likely represents a conservatism of on the order of a factor of 2-3 in the probability-weighted dose.

- A magma conduit is always assumed to be centered on a drift. This will tend to be conservative since a conduit not centered on a drift should intersect less waste containers. Based on the ratio of the area of the drifts to the area of the repository, this assumption is likely to be conservative by less than an order of magnitude.

- The major faults on either side of the repository have the potential to divert any magma around the repository. This has been conservatively ignored. The effect of accounting for such diversion around the repository would be to lower the probability of its occurrence. Given that the mean probability of occurrence of the scenario is only marginally above the value that should be considered in the TSPA, altering this assumption may eliminate the igneous scenario from further consideration.

3.7.1.3 Human Intrusion Scenario

The human-intrusion scenario is a hypothetical analysis of the potential effects of a drilling event at the site. In this analysis, a stylized drill hole is assumed to penetrate a waste package and continue to the saturated zone. The scenario therefore serves both to disrupt a waste package prematurely, and to provide a reasonably enhanced pathway to the saturated zone. DOE developed the human intrusion scenario for the TSPA-SR to be consistent with existing guidance in the proposed 40 CFR 197 (EPA99), the proposed version of 10 CFR 63 (NRC99), and the proposed version of 10 CFR 963 (DOE99a). The implementation of the regulatory requirements was conducted in the TSPA-SR as shown in Table 3-6 (TRW00a). The central feature for treatment of these requirements was to be consistent with the more conservative of the proposed requirements from the draft regulations. Most notably, the intrusion is assumed to occur at 100 years, consistent with the proposed NRC requirement (NRC99). Intrusion at later times, when (consistent with EPA99) a waste package might reasonably be more degraded to allow an unrecognized drilling penetration, was treated as a sensitivity case study.

As illustrated in Table 3-6, similarities between the proposed 40 CFR Part 197 and the proposed 10 CFR 63 consist of:

- the intrusion event is a single borehole that penetrates a waste container and continues to the saturated zone,
- doses to the driller are not considered,
- doses are evaluated only for gradual processes occurring at the repository, and
- borehole properties are consistent with current technical practices.

The primary differences between the two proposed regulations are:

- different dose criteria (15 vs. 25 mrem/yr), and
- the time of intrusion (100 years vs. a credible time for unrecognized penetration).

The DOE approach presented in Table 3-6 was to be consistent with the proposed regulations where they are consistent, and to consider both proposed regulations where they differ. The human intrusion standard in EPA's final regulations is unchanged in the aspects described in Table 3-6 (EPA01).

Table 3-6. Implementation of Regulatory Requirements in the TSPA-SR for Regulatory Requirements (Table adapted from TRW00a). Key differences between the NRC and EPA assumptions are indicated as underlined text.

NRC Base Assumptions (from Proposed 10 CFR Part 63)	EPA Additional and/or Conflicting Assumptions (from Proposed 40 CFR Part 197)	Conceptualization for TSPA-SR
Assumed intrusion is a drilling event.	Assumed intrusion is an acute and inadvertent drilling event.	Inadvertent drilling event.
Drilling result is a single, nearly vertical borehole that penetrates a waste package and extends down to the SZ.	Borehole penetrates a <u>degraded waste package</u>, and extends to the SZ.	Single vertical borehole from surface through a single waste package to the SZ.
Intrusion occurs 100 years after closure	Intrusion time should take into account the earliest time after disposal that a waste package could degrade sufficiently that current drilling techniques could lead to waste package penetration without recognition by the drillers.	Intrusion occurs at 100 years (a 10,000 year intrusion time is examined in a sensitivity simulation).
Borehole properties (diameter, drilling fluids) are based on current practices for resource exploration.	Borehole results from exploratory drilling for <u>ground water</u>. Borehole properties are consistent with current practices.	Borehole diameter consistent with an exploration ground water well.
Borehole is not adequately sealed to prevent infiltrating water.	<u>Natural degradation processes gradually modify the borehole</u>, the result is no more severe than the creation of a ground water flow path from the crest of Yucca Mountain through the potential repository and to the water table.	Infiltration and transport through the borehole assumes a degraded, uncased borehole, with properties similar to a fault pathway.
Hazards to the drillers or to the public from material brought to the surface by the assumed intrusion should not be considered.	Only consider releases through the borehole to the SZ; consider releases occur gradually through air and water pathways, not suddenly as with direct removal.	Ground water is only pathway considered.
A separate consequence analysis is required, identical to the performance assessment, except for the occurrence of the specified human intrusion scenario.	Unlikely natural processes and events are not included, but analysis could include disturbances by other processes or events that are likely to occur. Separate consequence-only analysis.	Intrusion borehole is applied to nominal case; effects of volcanism are not included.
Peak dose is not to exceed 25 mrem/yr. in the first 10,000 years.	Peak dose is not to exceed <u>15</u> mrem/yr., in the first 10,000 years.	Does not affect simulations.

The approaches used in TSPA-SR for evaluating these conditions are shown in Table 3-7. The analyses are based on a representation of an exploratory drilling intrusion, which leads to disruption of a waste package and an enhanced pathway through the unsaturated zone. The saturated zone and biosphere analysis are the same as in the nominal scenario.

3.7.2 Results of the TSPA-SR

The results of the TSPA-SR show the following characteristics. The results are composed of the combination of the nominal scenario and two igneous scenarios. The dose curves from these scenarios are weighted by their probabilities so they can be combined, as shown in Figure 3-2. These curves are then intended to be compared with proposed dose criteria, which are also shown in Figure 3-2. Human intrusion is treated as a separate scenario, which is not combined with the results from the nominal and igneous scenarios.

The nominal scenario produces nil dose values during the compliance period (<10,000 years). The only significant doses associated with the nominal scenario occur in the post-compliance period (>10,000 years). This is the result of complete containment of the waste by the design-basis engineered barrier system during the first 10,000 years.

TRW (TRW00a) states that doses in the first 2,000 years after closure are dominated by the eruption scenario. From 2,000 years until after 10,000 years, the doses are dominated by igneous intrusion followed by releases to ground water from the magma-disrupted waste packages. After 10,000 years, the dose curves are a more complicated function of the probability weighted doses from each of the three scenarios (nominal, eruption, and intrusion).

In all cases the mean dose rate from the combined scenarios is substantially less than the regulatory standards over 10,000 years. In addition, analyses presented in the TSPA-SR (TRW00a) show that none of the TSPA realizations exceeded any of the proposed regulatory criteria during the 10,000-year compliance period. As discussed in Section 3.7.1 above, the results within 10,000 years are likely to be extremely conservative because of the conservative treatment of igneous activity. Modified assumptions for repository behavior during interaction with magma have the potential to eliminate all calculated doses in the first 10,000 years.

It is interesting to contrast these results with earlier TSPA results presented in the TSPA-VA (DOE98). In the TSPA-VA, doses in the period less than 10,000 years were dominated by artificially introduced juvenile failures of the waste containers from manufacturing defects. These early doses have been eliminated in the TSPA-SR through a combination of an improved waste

Table 3-7. Technical Assumptions Implemented in the Human Intrusion Scenario in TSPA-SR (Table excerpted from TRW00a).

Issue	Key Component Affected	TSPA-SR Implementation
Borehole diameter	Infiltration Borehole Transport	Typical water well borehole has a diameter of 20.3 cm (8 in.)
Infiltration into borehole	Infiltration	Assumed infiltration rate distribution is based on modeled infiltration in the Yucca Mountain region for the glacial transition climate. Values at the high end of the distribution inherently include the possibility of surface water collection basin focusing.
Seepage into penetrated waste package	Infiltration Waste Mobilization	Volumetric flux is equivalent to infiltration rate times borehole area. Volume of drilling fluid is ignored.
Type of waste package penetrated	Waste Mobilization	Sampled from CSNF and co-disposed waste packages. Co-disposed packages contain both DSNF and HLW glass.
Thermal and geochemical conditions in waste package	Waste Mobilization	Assume temperature and in-package chemistry as calculated in nominal scenario. This assumes Well J-13 water and ignores any chemical effects of the drilling fluid.
Waste form degradation	Waste Mobilization	Waste in penetrated package is assumed to have perforated cladding from drilling disturbance.
Solubilization of radionuclides in water	Waste Mobilization	Infiltrating water can mix with waste in entire waste package. Solubility is based on temperature and in-package chemistry as in nominal scenario.
Borehole flow and transport properties	Infiltration Borehole Transport	Volumetric flux consistent with seepage into the waste package. Transport properties consistent with a UZ fault pathway.
Borehole location	Infiltration SZ Transport	Random over the footprint of the potential repository. Uncertainty in location is captured in infiltration rate and location that radionuclides enter the SZ.
Borehole length	Borehole Transport	Borehole length from the potential repository to SZ conservatively assumes water level consistent with glacial transition climate.
SZ	SZ Transport	Assume SZ flow and transport properties identical to nominal scenario.
Biosphere processes	Biosphere	Assume exposure pathways and receptor characteristics identical to nominal scenario.

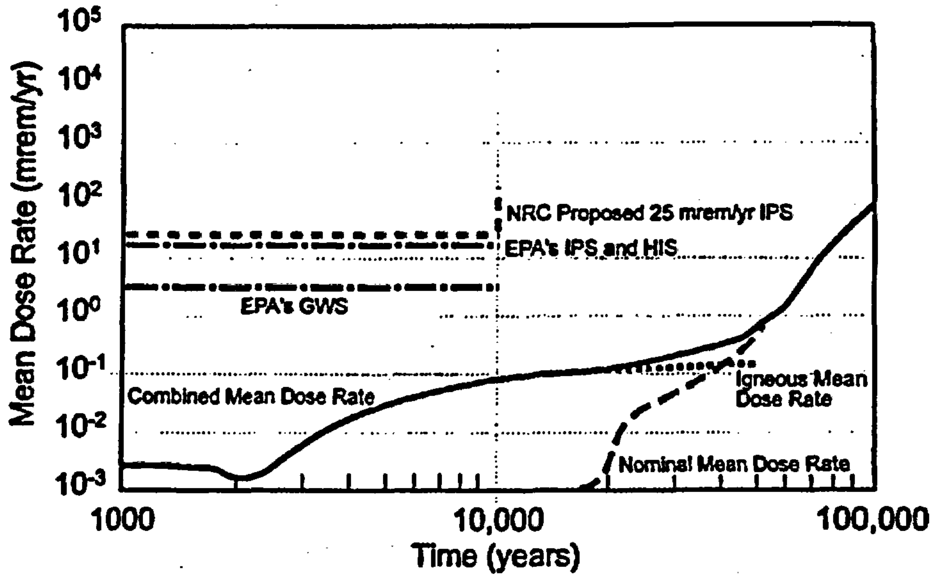

Figure 3-2. Comparison of Radiation Protection Standards with Expected Values of TSPA-SR Calculations for a Repository at Yucca Mountain for Nominal and Igneous Scenarios (Figure adapted from TRW00a)

package design, and improved, more realistic modeling of juvenile failures associated with the new design. However, in the assessments of doses within 10,000 years these juvenile failures from manufacturing defects have been replaced in the TSPA-SR by juvenile failures associated with the igneous scenarios, with their associated assumptions about early complete destruction of the waste containers, and very conservative assumptions for eruption characteristics.

Mean dose-rate results from the human-intrusion scenario are presented in Figure 3-3. As discussed in Section 3.7.1, the base case represents a conservative assumption of intrusion at 100 years, in keeping with NRC guidance (NRC99). Mean dose-rate results from a sensitivity case are also shown on the figure, in which the intrusion occurs at 10,000 years in keeping with EPA guidance (EPA99). The mean dose-rate is not significantly higher at 100 years than at 10,000 years. The mean dose-rate is well below the relevant regulatory standards at all times.

3.8 DOE's Current Program Costs

The cost figures in Table 3-8 reflect DOE's most recent estimates (DOE01a) for both historical costs for the repository program to the year 2000, and projected costs through the closure and decommissioning phases. These cost estimates are adjusted to a common basis of constant dollars

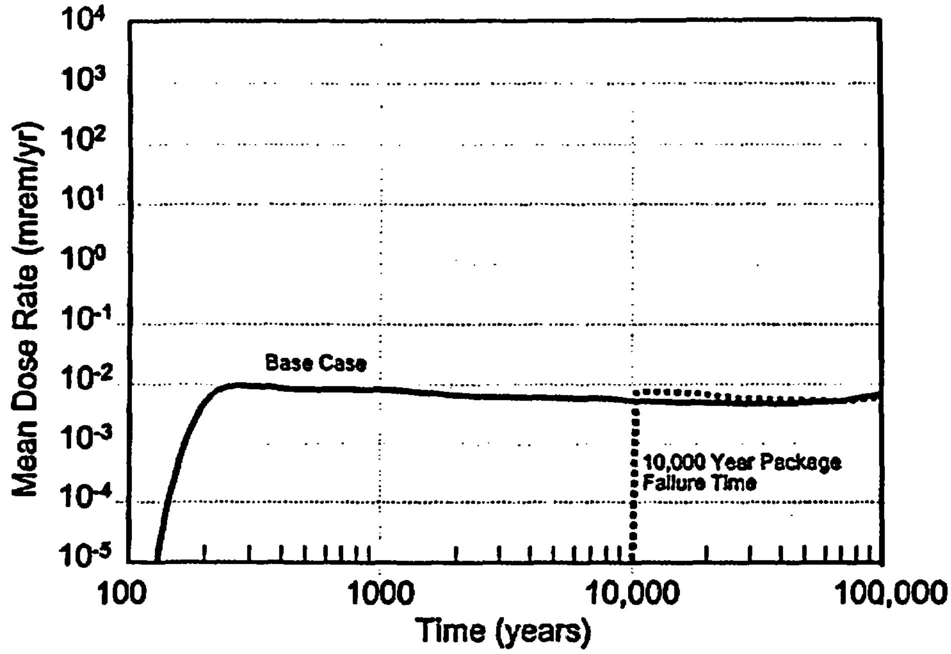

Figure 3-3. Expected Values of TSPA-SR Calculations for a Repository at Yucca Mountain for the Inadvertent Human Intrusion Scenario (Figure adapted from TRW00a)

at year 2000. Table 3-8 retains DOE's cost estimates that were presented in the Viability Assessment documents (DOE 98) for site characterization work, since comparable detail for these expenditures were not given in the newest cost estimates.

Cost figures indicate that the combined cost of the EDA II design waste package and drip shield fabrication is estimated at $13.2 Billion. Emplacement costs for the waste package and drip shields is estimated at an additional $8.2 Billion (DOE01a, p. 3-10), giving a total cost of implementing this component of the EDA II design of $21.4 Billion. This sum is considerably higher than the cost of planned additional site characterization investigations and reflects DOE's choice to use enhanced engineering to reduce or eliminate uncertainties in the behavior of the natural barrier.

As discussed in Chapters 4 and 5 of this document, overly conservative assumptions included in performance assessment scenarios produce dose projections that will be considerably higher, by orders of magnitude, than what should be expected for more realistic assessments. Typically, performance assessment analyses are deliberately framed with conservative assumptions. This is done to provide a measure of confidence that the assessments represent a conservative, and

Table 3-8. Estimates of Costs for the Yucca Mountain Program*

1. Historical Total, Mined Repository FY 1983-2000 (DOE01a TSLCC, p. 1-2)			$ 8.2 B
2. Complete Work to License Application (DOE01a TSLCC, p. 1-3):			$ 0.8 B
3. Details of Completion Work, FY 1999-2002 (DOE98, Vol.4, Table 6-2)			
Site Investigations (total)		$ 189.2 million	
Nye County	$15.6 million		
SZ data analysis	3.4		
SZ modeling	2.2		
Repository Design		296.5	
Performance Assessment		63.6	
Final analyses	8.3		
EIS		64.1	
Site Recommendation		2.9	
Licensing		76.6	
Field Operations		106.1	
Other Support		277.3	
Financial Assistance		61.8	
		$1138.1 million	
4. Repository (2003-2119) (DOE01a, p. 3-8)			$35.4 B
Licensing (2003-2006)		$ 1.3 billion	
Pre-Emplacement Construction (2006-2010)		4.4	
Emplacement Operations (2010-2041)		19.7	
Monitoring (2041-2110)		6.0	
Closure and Decommissioning (2110-2119)		4.0	
		$ 35.4 billion	
5. Design Options to the VA Repository			$13.2 B
Drip Shields and Backfill Fabrication (DOE01a, p. 13-2)			
6. Total Repository Cost (1982-2119) (DOE01a, p. 3-8)			$36.3 B
7. Total Program Cost (DOE01, p. 1-2) $49.3 B + Historical Costs $8.2B			$57.6 B

* Costs from the Total System Life Cycle Cost Estimate (DOE01a) are in constant year 2000 dollars.

perhaps "worst case" analysis so that the acceptability of the disposal system's projected performance can be evaluated with a greater public acceptance and a fundamentally conservative performance case for the licensing process. Counterbalancing this conservative assessment bias must be a recognition that excessive conservatism in framing performance scenarios can lead to design choices which may be significantly more "robust" than necessary to provide a reasonable

expectation of satisfactory performance. Greatly increased costs can result if the conservative bias in framing performance scenarios is taken to excess. Chapters 4 and 5 of this document discuss the evolution of DOE's performance assessment approaches for the Yucca Mountain repository, and the conservatism incorporated in them, as well as the contrast between these performance scenario assumptions and the "reasonable expectation" approach inherent in the Agency's standard.

7.0 SUMMARY DEMONSTRATION THAT THE EPA STANDARDS HAVE NO COST IMPACTS ON THE YUCCA MOUNTAIN PROGRAM AND REPOSITORY

7.1 Principal Bases for Findings of No Cost Impacts

This Economic Impact Assessment (EIA) has demonstrated that DOE's strategy for development and design of a possible repository at Yucca Mountain has evolved to the point that EPA's 40 CFR Part 197 standards will have no impact on the total life-cycle costs of the repository. This has been demonstrated through an examination of the factors that influenced evolution of repository design and a review and analysis of DOE's performance assessments. The principal factors that provide the basis for a finding of no-cost impact of the standards are:

- The DOE plans for repository design strategy, data acquisition, and budget allocations and requirements have been established independent of the EPA standards. DOE's plans and cost estimates reflect, as suggested above, expenditures and activities not needed as a direct consequence of the EPA standards.
- Earlier performance assessment results (TSPA-VA), which are based on highly conservative assumptions that would not be used under principles of Reasonable Expectation, suggest expectation of compliance with EPA's IPS, HIS and GWS limits. More recent performance assessment results (TSPA-SR) show even greater margins for compliance with the EPA standards than the TSPA-VA results. The newer design (EDA II) is augmented to produce improved expected performance for the nominal case, and design features have been selected to reduce the potential for significant issues during licensing reviews. Figure 3-2 demonstrates dramatically the assertion that EPA's standards have no impact on Yucca Mountain program costs. Under the nominal scenario there is no release during the time period over which the IPS, HIS, and GWS would apply. Releases may only be expected to occur if violent volcanic activity occurs at the site, and this is unlikely considering the volcanic history of the site. The magnitude of releases associated with volcanic activity are very conservatively estimated in the TSPA-SR in comparison to reasonably expected conditions.
- The data and analysis requirements for assessing compliance with the ground water protection and human-intrusion standards are the same as those required for assessing compliance with the fundamental and essential individual-protection standard. The ground water protection standard and the human-intrusion standard therefore impose no incremental costs.

These factors are discussed in more detail in Sections 7.1.1 through 7.1.3. Section 7.2 discusses alternative standards and their relationship to repository performance, and Section 7.3 provides an overall summary and conclusions.

7.1.1 Evolution of the Repository Design and Roles of Natural and Engineered Features

The initial repository design concept, described in the Site Characterization Plan (SCP) issued in 1988, anticipated that natural features of the repository system, such as very low rates of water movement in the unsaturated zone (UZ), would dominate repository performance. Engineered features would be the minimum necessary to meet the subsystem performance requirements of the Nuclear Regulatory Commission's (NRC) 10 CFR Part 60 standards, such as substantially complete containment of radionuclides within the waste package for 300-1,000 years.

In contrast to SCP expectations, acquisition and analysis of subsequent site characterization data revealed that the SCP's performance expectations for the natural system would not be achieved, e.g., there are paths for rapid movement of water through the UZ and rates of ground water infiltration were higher than earlier thought. Consequently, the performance capabilities of the engineered features of the system have been revised from the SCP concept to one in which the engineered features play the dominant role in disposal system performance during the regulatory period: more specifically, the use of highly corrosion-resistant waste package wall materials and drip shields to defer contact of the waste packages by water that drips into the repository. The design features are intended to provide defense-in-depth for performance and to minimize uncertainties and technical issues associated site performance that could become contentious issues during the licensing process.

The inversion of performance roles of the natural and engineered features of the repository system has evolved as a result of site characterization findings, guidance from external reviews such as those of the Nuclear Waste Technical Review Board, and interactions with NRC staff which provide guidance on licensing requirements. **The evolution has been independent of the EPA standards, the major components of which have remained essentially unchanged since the 1985 promulgation of the generic 40 CFR Part 191 standards for geologic disposal.**

7.1.2 DOE's Use of Performance Evaluations

The Department has used a series of Total System Performance Assessments (TSPA) to guide selection and prioritization of site characterization activities, to guide selection of engineered features and parameters, and to make projections of repository safety performance. TSPA models and methodology have evolved in parallel with the evolution of the site database and engineered design concepts.

The TSPA for the Viability Assessment in 1998 (TSPA-VA) was the first TSPA for a potential repository system at the Yucca Mountain site. Despite use of conservative models and assumptions, TSPA-VA results for the base case using average parameter values showed dose rates at 10,000 years, for a dose receptor at 20 km distance from the repository and with characteristics comparable to EPA's Reasonably Maximally Exposed Individual (RMEI), that were two orders of magnitude lower than the EPA's individual-protection standard of 15 mrem/yr CEDE. More reasonable assumptions in framing these scenarios and the associated conceptual models would show lower projected doses of at least several orders of magnitude.

In response to reviews of the TSPA-VA which found that there were uncertainties in the models and results that could produce significant technical issues for licensing reviews, DOE subsequently adopted the current engineered design, EDA II, which has as principal features use of titanium drip shields and a highly corrosion resistant waste package outer wall. This engineered barrier design concept is significantly augmented in comparison with the VA design. TSPA-SR estimates of performance for this design indicate that, under expected conditions, there will be no radionuclide releases and no potential for radiation doses for more than 10,000 years after repository closure, unless the repository is disrupted by volcanic activity. Even in that extreme occurrence, the repository is shown in the TSPA-SR not to exceed the exposure limits. The performance scenarios and conceptual models in the TSPA-SR were also developed using conservative assumptions, although more realistically than the TSPA-VA approaches. Expected releases would be considerably lower for even more realistic assessments.

All of the above actions were completed or underway by the time NRC put forth its proposed 10 CFR Part 63 regulations in February 1999 and EPA put forth its proposed 40 CFR Part 197 standards in August 1999. In particular, DOE program plans, repository design concepts, and program cost estimates had all been documented before EPA's proposed standards were issued for public comment.

7.1.3 Impact of the EPA Standards on Data and Analysis Requirements

The third perspective included in this EIA is an examination of the data and analysis requirements imposed by the individual-protection, ground water protection, and human-intrusion standards. Each of these components of the standard requires a quantitative evaluation of projected repository performance, and a database of performance parameters for the repository's natural and engineered features, for compliance assessment. This EIA demonstrates that the data and analysis requirements for assessing compliance with the ground water protection and human-intrusion standards are the same as those required for assessing compliance with the fundamental and

essential individual-protection standard. The ground-water-protection and human-intrusion provisions therefore impose no incremental cost impacts.

7.2 Comparative Impacts of Alternative Dose Limits for the Individual-Protection Standard

An important issue in developing the individual-protection standard has been comparative impacts of alternative dose limits, e.g., 15 mrem/yr versus 25 mrem/yr. Figure 3-2 (which is the same as Figure ES-1) shows the performance projections EDA II designs given in TSPA-SR.

As seen in Figure 3-2, the EDA II repository design demonstrates performance such that projected doses are significantly less than either the 15 mrem/yr or the 25 mrem/yr dose limit. Indeed, the only doses that occur in the first 10,000 years are the result of potential volcanic activity scenarios that are very conservative. It is therefore evident that selection of a 15 mrem/yr dose limit rather than a 25 mrem/yr limit will not impose any additional cost impacts on the repository. This is a highly significant finding in that the 15 mrem/yr CEDE dose limit is consistent with the recommendations of the National Academy of Sciences and regulatory precedents for deep geologic disposal applications (WIPP).

As noted in Section 4 of this document, the TSPA-VA evaluations of potential VA-repository performance used highly conservative models and assumptions, such that the actual expected performance of a VA repository would be at least several orders of magnitude better than was reported in the TSPA-VA results. Similarly, with the enhanced engineered barrier system design for EDA II, the performance as evaluated in the TSPA-SR is significantly better than that projected for the VA. No radionuclide releases are expected to occur for more than 10,000 years, and even if highly-improbable violent strombolian eruption occurs, the repository design easily meets either the 15 mrem/yr or the 25 mrem/yr limit. Performance scenarios in the TSPA-SR analyses and the models used to evaluate them, although different in many respects from the TSPA-VA, are still very conservative. Analyses using more realistic, yet still defensible, assumptions would show performance results considerably better than the one presented in the TSPA-SR.

The projections of repository performance for the EDA II design are shown in Figures 3-2 and 3-3 compared to the EPA and proposed NRC regulations. As can be seen in these figures, and as noted above in the discussion of the alternative dose limits, performance in all cases considered is significantly better than required by the standards. The highly conservative igneous intrusion and eruptions considered in the TSPA-SR show dose estimates one to two orders of magnitude below

the limits imposed by the standards; the expected performance (nominal scenario, excluding volcanic events) within the regulatory time period for the EDA II repository shows no releases relevant to the proposed standards.

As discussed in Section 3.4, the EDA II design and the refinement of repository strategy serve primarily to ease concerns for uncertainties and technical issues that were associated with the TSPA-VA methodology that could be difficult to resolve in licensing reviews, and to add to the performance margin with use of drip shields to implement defense-in-depth concepts. The new design was not driven by requirements in the EPA rule, but rather as a means to compensate for uncertainties in performance projections.

7.3 Summary and Conclusions

The need to demonstrate compliance with the individual-protection standard is fundamental to assurance of protection of public health and safety for deep geologic disposal. There is also need, for geologic disposal, to provide protection in the event of inadvertent future human intrusion and there is need to protect ground water resources for future generations. Imposition of, and compliance with, the HIS and GWS standards is essential for consistent and comprehensive application of EPA policy concerning ground water protection and for appropriate application of generic principles set forth in 40 CFR Part 191 to the Yucca Mountain setting.

As shown in this document, the evolving understanding of the Yucca Mountain site characteristics, and the resulting information base needed to provide defense-in-depth and to reduce uncertainties during licensing reviews has driven the Yucca Mountain program data acquisition program and evolution of design concepts. Because of site-specific conditions, DOE's strategy for development and design of a possible repository at Yucca Mountain has evolved so that EPA's 40 CFR Part 197 standards will have no impact on the costs of the repository program. This document has also shown that EPA's generic 40 CFR Part 191 standards did not influence evolution of the Yucca Mountain program or the repository design. Moreover, as illustrated by Figures 3-2 and 3-3, expected performance for the current repository design is significantly better than is required by the EPA standards for HIS, GWS, and IPS.

The information base required for demonstrating compliance with the HIS and GWS standards is the same as that required for demonstrating compliance with the individual-protection standard. Costs and effort above those needed to evaluate compliance with the IPS therefore do not have to be incurred to evaluate compliance with the HIS and GWS standards.

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CERTIFICATE OF SERVICE

I, the undersigned, hereby certify that a true and correct copy of "Supplemental Appendix Volume II" was served this 6th day of June, 2003, via First Class U.S. Mail, postage prepaid to the following individuals:

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