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Public Health and Environmental Radiation Protection Standards for Yucca Mountain, Nevada - Final 40 CFR 197

Evaluation of Potential Economic Impacts of 40 CFR Part 197

(ECONOMIC IMPACT ASSESSMENT)

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* NOTE: This document has been revised to correct minor errors which were contained in the version placed in the public docket for the Yucca Mountain Rule (docket #A-95-12, V-B-2). A listing of those changes is located at the end of this document.

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BDCF	Biosphere Dose Conversion Factor
BID	Background Information Document
BWR	Boiling Water Reactor
CAM	Corrosion Allowance Material
CEDE	Cumulative Effective Dose Equivalent
CFR	Code of Federal Regulations
CRM	Corrosion Resistant Material
CSNF	Commercial Spent Nuclear Fuel
DEIS	Draft Environmental Impact Statement
DOE	Department of Energy
EBS	Engineered Barrier System
EDA	Enhanced Design Alternative
EDE	Effective Dose Equivalent
EIA	Economic Impact Analysis
EnPA	Energy Policy Act
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
ESF	Exploratory Studies Facility
FEHM	Finite Element Heat and Mechanical Model
GWS	Ground Water Protection Standard
HIS	Human-Intrusion Protection Standard
HLW	High-Level Waste
ICRP	International Commission on Radiation Protection
IPS	Individual-Protection Standard
LADS	License Application Design Selection
MTHM	Metric Tonnes of Heavy Metal
MTU	Metric Tonnes of Uranium
MWd	Megawatt Days
NAS	National Academy of Sciences
NRC	Nuclear Regulatory Commission
NWPA	Nuclear Waste Policy Act
NWPAA	Nuclear Waste Policy Amendments Act
NWTRB	Nuclear Waste Technical Review Board
OCRWM	Office of Civilian Radioactive Waste Management (DOE)
PWR	Pressurized Water Reactor
RA	Reasonable Assurance
RE	Reasonable Expectation
RMEI	Reasonably Maximally Exposed Individual
SCC	Stress Corrosion Cracking
SCP	Site Characterization Plan
SDWA	Safe Drinking Water Act
SR	Site Recommendation
SZ	Saturated Zone
TSLCC	Total System Life Cycle Costs

TSPA	Total System Performance Assessment
UZ	Unsaturated Zone
VA	Viability Assessment
WIPP	Waste Isolation Pilot Plant

EXECUTIVE SUMMARY

This Economic Impact Assessment (EIA) demonstrates that DOE's strategy for development and design of a possible repository at Yucca Mountain has evolved so that the EPA's 40 CFR Part 197 standards will have no impact on costs of the repository or the repository development program. It also shows that the EPA's generic 40 CFR Part 191 standards, as well as the 40 CFR Part 197 site-specific standards, did not influence evolution of the DOE program or the repository design.

The EIA analysis uses three major, converging perspectives to support the conclusion that the EPA standard for Yucca Mountain does not impose additional costs on the DOE program:

- An historical perspective in Chapter 3 traces the evolution of the repository design from principal reliance for safety performance on natural features to principal reliance on engineered features and the factors that influenced it. This discussion concludes that the inversion of performance roles of the natural and engineered features of the disposal 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 evolution of strategy for dealing with uncertainties. **This discussion demonstrates that evolution of the repository design 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.**

- A performance assessment perspective in Chapter 4 traces the evolution of strategy to achieve performance, the evolution of identification and characterization of factors that contribute to performance, and the approach to identifying and reducing uncertainties that are important to demonstration of compliance with standards. **The discussion includes DOE estimates of performance for the current repository design which show that, under nominal conditions, there will be no radionuclide releases and no potential for radiation doses for more than 10,000 years after repository closure.**

  The new repository design was not developed to respond to any provisions of the EPA standard, but rather to reduce or eliminate uncertainties in the very conservative performance assessments of the previous design. Relative to the "reasonable expectation" approach to implementation that is included in the standard (described in more detail in this document), the previous assessments of the older design are considered to illustrate the impact of reasonable expectation on repository design and performance assessments.

- An information-needs perspective assesses the data and analyses needed to address the IPS, GWS, and HIS components of the EPA standard, with emphasis on whether resources beyond those needed to address the individual-protection standard, which is fundamental to radiation protection, are needed to address the GWS and HIS standards. **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 standard and the human-intrusion standard, therefore, impose no incremental cost impacts.**

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

A contentious issue in developing the individual-protection standard has been comparative impacts of alternative dose limits, e.g., 15 millirem/year (mrem/yr) versus 25 mrem/yr. Figure ES-1, which shows the performance projections for the newest repository design (EDA II), under conditions of expected performance, provides an important perspective on the dose limit issue. Doses in the period less than 10,000 years are entirely the result of a very low probability (the mean annual probability is 1.6×10^{-8}) potential igneous disruption of the disposal facility. A very small downward shift in estimates of probability would eliminate this scenario from consideration altogether. In addition, the consequences associated with potential releases from igneous activity appears to be treated in an extremely conservative manner. Alternative assumptions are possible that would eliminate releases associated with igneous activity entirely, even in the unlikely event that such activity occurs.

The nominal scenario represents an assessment of the function of the repository when only gradual degradation processes occur. This scenario does not lead to any releases in the first 10,000 years, despite a significant level of conservatism built into the model. The current model of the current repository design shows lower consequences at longer times than did earlier iterations of the TSPA. Significantly, even these earlier iterations (e.g. TSPA-VA), which contained extremely conservative assumptions about juvenile failures of waste containers, were able to comfortably comply with either of the alternative individual-protection standards.

As seen in Figure ES-1, 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. Furthermore, for nominal behavior of the repository, there are no projected doses during the first 10,000 years. 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

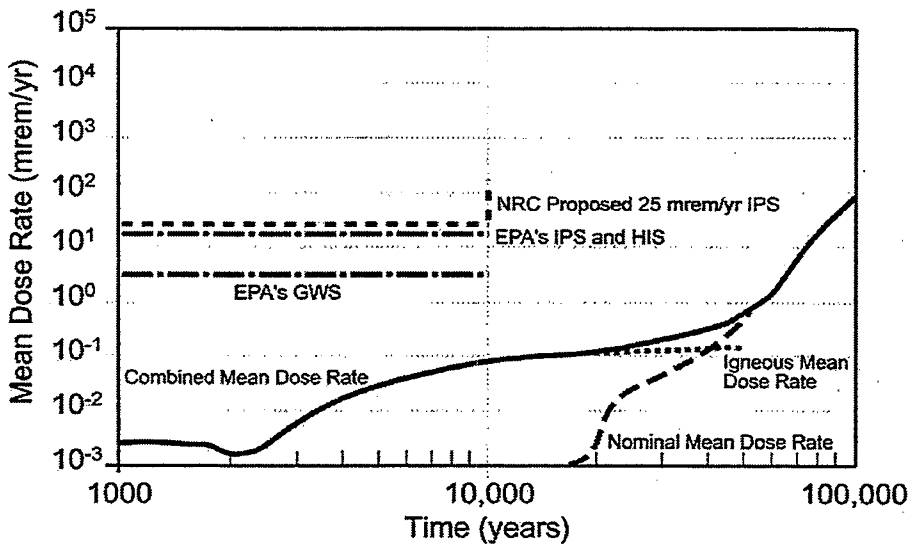

Figure ES-1. Comparison of Radiation Protection Standards with Expected Values of TSPA-SR Calculations for a Repository at Yucca Mountain for Nominal and Igneous Scenarios.

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.

Conclusions

The information presented in this EIA has demonstrated that the design of a repository for disposal of radioactive wastes at Yucca Mountain has evolved without having been affected by the EPA standards. The standards have been demonstrated to have no impact on repository program costs, and nominal performance for the current repository design would result in no radiation doses for more than 10,000 years. Additionally, the difference between a 25 mrem/yr dose standard and a 15 mrem/yr standard is insignificant to program costs and performance evaluations.

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1.0 EVOLUTION OF REGULATORY REQUIREMENTS

This chapter describes the basis for this rulemaking and provides a brief history of EPA's regulatory authority and prior rulemaking actions concerning disposal of radioactive wastes. It demonstrates that this rulemaking is derived from provisions of the Energy Policy Act of 1992. Standards for individual protection and human intrusion are based on recommendations made by the National Academy of Sciences, and ground water protection standards are based on the Safe Drinking Water Act and regulatory precedents.

1.1 EPA Action and Authority

The U.S. Environmental Protection Agency (EPA), pursuant to Section 801 of the Energy Policy Act of 1992 (EnPA) has issued a rule, 40 CFR Part 197, which contains standards for the protection of the public from releases of radioactive materials stored or disposed of in a repository at the Yucca Mountain site in Nevada. This document was prepared to evaluate the economic impact of this rule.

The rule contains three principal component standards: Individual-Protection Standard (IPS), Human-Intrusion Standard (HIS), and Ground Water Protection Standards (GWS). Details of the evolution of the rule and these standards are described in Section 3 of this document.

1.2 Role of this Document

This document describes, in detail, the basis for, and results of, the assessment of economic impacts of the standards on the costs of storage and disposal of radioactive wastes at Yucca Mountain.

The document traces the history of evolution of the Yucca Mountain repository design, from the early use of a small, thin-walled canister, and repository features that were expected to dominate safety performance reflecting ground water travel times of tens of thousands of years (circa 1988), to the current design, in which engineered features (consisting of drip shields and large, multi-walled waste packages) dominate performance, and are expected to maintain radionuclides in isolation for at least 10,000 years (TRW00). The document also discusses the evolution of performance assessments and the inversion of roles of engineered and natural barriers, the EPA's "Reasonable Expectation" approach to performance projections and compliance decisions, and the overall impact of the standards on Yucca Mountain costs.

This document will demonstrate that the repository design evolved not in response to the expected provisions of the standard, but in response to improved understanding of the natural and engineered barrier interactions and performance expectations, as a result of 12 years of site characterization, performance assessment and design activities performed by the DOE. The uncertainties identified by DOE's efforts over this period could be addressed by either developing enhanced engineering design alternatives to reduce or eliminate the uncertainties, or by investing time and resources in more extensive characterization and testing studies. DOE has leaned toward enhanced engineering, at least in part because inherently some uncertainties about the characteristics and behavior of the natural system may not be amenable to unequivocal reduction or elimination even with extensive field and laboratory testing.

1.3 40 CFR Part 197

The remainder of this chapter describes the evolution of the 40 CFR Part 197 regulation and the rationale underlying its development. The U.S. Environmental Protection Agency (EPA) is responsible for developing and issuing environmental standards and criteria to ensure that public health and the environment are adequately protected from potential radiation impacts. The regulation contains site-specific environmental standards to protect public health from releases from radioactive materials disposed of or stored in the potential repository to be constructed at Yucca Mountain in Nevada**. These standards provide the basic framework to control the long-term storage and disposal of radioactive wastes at Yucca Mountain.

Other radioactive materials that could be disposed of in the Yucca Mountain repository include highly radioactive low-level waste, known as greater-than-Class-C waste, and excess plutonium resulting from the dismantlement of nuclear weapons.

Emphasis in this document is on the major components of the Yucca Mountain standard, namely the Individual-Protection Standard (IPS), the Human-Intrusion Standard (HIS), and the Ground Water Protection Standard (GWS). In reviewing the development of the current standard attention will be devoted primarily to these components.

1.4 Legislative History

EPA has the authority to set generally applicable environmental standards for radioactive releases under the Atomic Energy Act (AEA) of 1954, as amended (AEA54), and the President's

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** No decision has been made regarding the acceptability of Yucca Mountain for storage or disposal. In this document, the characterization of the Yucca Mountain repository as "potential" is often omitted but always intended.

Reorganization Plan No. 3 of 1970 (NIX70). The basic authority under the AEA, as transferred to the EPA by Reorganization Plan No 3, includes the mandate of:

> *...establishing generally applicable environmental standards for the protection of the general environment from radioactive materials. As used herein, standards mean limits on radiation exposures or levels, or concentrations or quantities of radioactive material, in the general environment outside the boundaries of locations under the control of persons possessing or using radioactive materials (AEA54).*

In 1982, the Nuclear Waste Policy Act (NWPA) (Public Law 97-425) established formal procedures regarding the evaluation and selection of sites for geologic repositories, including procedures for the interaction of state and Federal Governments. The Act assigned the U.S. Department of Energy (DOE) the responsibility of siting, building, and operating an underground geologic repository for the disposal of these wastes, established provisions for the selection of at least two independent repository sites, and limited the quantity of wastes to be disposed of in the initial repository to 70,000 metric tons of heavy metal (MTHM)[***]. The NWPA also reiterated the existing responsibilities of the Federal agencies involved in the national program (see AEA authority above) and provided a timetable for several key milestones to be met by the Federal agencies. The NWPA also directed that EPA, pursuant to its authorities under other provisions of law, was required to:

> *by rule, promulgate generally applicable standards for the protection of the general environment from off-site releases from radioactive material in repositories (NWP83).*

The basic authority for EPA to establish environmental standards for the repository effort originates from these sources.

In September 1985, EPA published 40 CFR Part 191, "Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes" (EPA85). These standards were generic and intended to apply to all sites for the deep geologic disposal of high-level radioactive waste. In 1987, the U.S. Court of Appeals for the First Circuit responded to a legal challenge by remanding Subpart B of the 1985 standards (the disposal standards) to the Agency for further consideration. This regulation, which is of considerable importance to the development of 40 CFR Part 197, will be discussed further in the next section.

*** This is a measure of the uranium content of the spent nuclear fuel to be emplaced in the repository.

In December 1987, Congress enacted the Nuclear Waste Policy Amendments Act (NWPAA). The 1987 Amendments Act redirected the nation's nuclear waste program to evaluate the suitability of only the Yucca Mountain site as the location for the first high-level waste and spent nuclear fuel repository (NWP87). An important program change instituted by the Amendments Act was establishment of the Nuclear Waste Technical Review Board (NWTRB). The NWTRB was charged with providing independent technical and scientific review of the OCRWM program. It consists of experts in various disciplines (about 10, but limited to 22) and has a small support staff. Members of the NWTRB are appointed by the President of the United States. The opinions and recommendations of the NWTRB have played a significant role in the development of the repository design, as will be pointed out in other sections of this document.

The NWPAA, while dramatically changing the scope and focus of the repository effort, did not affect or alter EPA's role, i.e., to develop the environmental standards for deep geological disposal.

In October 1992, the Waste Isolation Pilot Plant Land Withdrawal Act (WIPP LWA, Public Law 102-579) was enacted. While reinstating certain sections of the Agency's 1985 disposal standards, the Act exempted the Yucca Mountain site from these generic disposal standards (WIP92). In its stead, the Energy Policy Act (EnPA) of 1992 was enacted (Public Law 102-482), which established EPA's authority to develop standards for environmental releases specific to Yucca Mountain.

Section 801 of the EnPA directed EPA to promulgate standards to ensure protection of public health from releases of radioactive material from a deep geologic repository to be built at Yucca Mountain (EnP92). EPA must set standards to ensure protection of the health of the public. The EnPA also required EPA to contract with the National Academy of Sciences (NAS) to advise the Agency on the technical bases for the Yucca Mountain standards. These EPA standards will apply only to the Yucca Mountain site and are to be developed based upon and consistent with the findings and recommendations of the NAS:

> *...the Administrator shall, based upon and consistent with the findings and recommendations of the National Academy of Sciences, promulgate, by rule, public health and safety standards for protection of the public from releases from radioactive materials stored or disposed of in the repository at the Yucca Mountain site. Such standards shall prescribe the maximum annual effective dose equivalent to individual members of the public from releases to the accessible environment from radioactive materials stored or disposed of in the repository* (EnP92).

1.5 40 CFR Part 191

The 1985 EPA standards for the management and disposal of spent nuclear fuel and high-level and transuranic waste were divided into two main sections, Subparts A and B (EPA85). Subpart A, which addressed the management and storage of waste, limited radiation exposure to any member of the general public to 25 millirem (mrem) to the whole body and 75 mrem to any critical organ for disposal facilities operated by the Department of Energy, but not regulated by the NRC or an Agreement State. For facilities regulated by the NRC or an Agreement State, the standards endorsed the annual dose limits given in the environmental standards for the uranium fuel cycle (40 CFR Part 190): 25 mrem to the whole body, 75 mrem to the thyroid, and 25 mrem to any critical organ (EPA77). The 25 mrem dose limit was based on a dosimetry system dating from the 1977 International Commission on Radiation Protection recommendations (ICR77), which are now outdated. The ICRP dose limit has since been revised to be consistent with current dosimetry, so that the 15 mrem/yr CEDE dose limit in the proposed 40 CFR Part 197 rule is essentially the same as the 25 mrem/yr limit for the 1977 dosimetry.

Subpart B imposed limits associated with the release of radioactive materials into the environment following closure of the repository. The key provisions of Subpart B (EPA85) were:

- Limits on cumulative releases of radioactive materials into the environment during the 10,000 years following disposal (§191.13)
- Assurance requirements to compensate for uncertainties in achieving the desired level of protection (§191.14)
- Individual exposure limits based on the consumption of ground water and any other potential exposure pathways for 1,000 years after disposal (§191.15)
- Ground water protection requirements in terms of allowable radionuclide concentrations and associated doses for 1,000 years after disposal (§191.16)
- Consideration of inadvertent human intrusion into the repository (Appendix B)

Under §191.15 and §191.16 of Subpart B, the annual dose to any member of the general public was limited to 25 mrem to the whole body and 75 mrem to any critical organ (under the outdated dosimetry system). The ground water concentration for beta or gamma emitters was limited to the equivalent yearly whole body or organ dose of 4 mrem. The allowable water concentration for alpha emitters (including radium-226 and radium-228, but excluding radon) was 15 picocuries/liter (pCi/L). For radium-226 and radium-228 alone, the concentration limit was

5 pCi/L. Appendix A of the standards provided acceptable radionuclide-specific cumulative release limits.

In March 1986, five environmental groups led by the Natural Resources Defense Council and four States filed petitions for a review of 40 CFR Part 191 (USC87). These suits were consolidated and argued in the U.S. Court of Appeals for the First Circuit in Boston. The main challenges concerned:

- Violation of the Safe Drinking Water Act (SDWA) underground injection section,
- Inadequate notice and comment opportunity on the ground water protection requirements, and
- Arbitrary standards, not supported in the record, or not adequately explained.

In July 1987, the Court rendered its opinion and noted three findings against the Agency and two favorable judgments. The Court's action resulted in the remand of Subpart B, the disposal standards. The Court began by looking at the definition of "underground injection." In the view of the Court, the method envisioned by DOE for disposal of radioactive waste in underground repositories would "...likely constitute an underground injection under the SDWA."

Under the SDWA, the Agency is required to assure that underground sources of drinking water will not be endangered by any underground injection. With regard to such potential endangerment, the Court supported part, but not all, of the Agency's approach. Inside the controlled area, the Court ruled that Congress—through the EPA—had allowed endangerment of ground water. However, the Court accepted EPA's approach of using the geological formation as part of the containment. This aspect of the Court's opinion is important in that it recognizes that a portion of the area around the footprint of the geologic repository could be considered to be an integral part of the repository system and could be dedicated to that use. This area was designated as a controlled area in the rule and was limited to an area of 100 square kilometers (sq. km.).

Outside the controlled area, the Court found that §191.15 would allow endangerment of drinking water supplies. In the context of the SDWA, "endangerment" was considered when doses higher than those allowed by the Primary Drinking Water Regulations could occur. In §191.15, an annual dose of 25 mrem to the whole body and 75 mrem to any critical organ from all pathways is permitted, whereas existing EPA regulations promulgated under the SDWA allowed an annual dose of 4 mrem from drinking water. Although the Court recognized that an exposure level less than 4 mrem could result from the ground water pathway, it rejected this possibility because the

Agency stated that radioactivity could eventually be released into the ground water system near the repository and that substantially higher doses could result. Therefore, the Court decided that a large fraction of the 25 mrem limit could be received through the ground water exposure pathway. Accordingly, the Court found that the Part 191 standards should either have been consistent with the SDWA or the Agency should have justified the adoption of a different standard.

The Court stated that the Agency was not necessarily incorrect in promulgating the proposed standards. However, it noted that the Agency never acknowledged the interrelationship of the SDWA and the Part 191 standards nor did it present a reasonable explanation for the divergence between them. The Court also supported the petitioner's argument that the Agency had not properly explained the selection of the 1,000-year limit for individual-protection requirements (§191.15). The Court indicated that the 1,000-year criterion was not inherently flawed, but rather that the administrative record and the Agency's explanations did not adequately support this choice. The criterion was remanded for reconsideration, and the Agency was directed to provide a more thorough explanation for its basis.

Finally, the Court found that the Agency did not provide sufficient opportunity for notice and comment on §191.16 (Ground Water Protection Requirements), which was added to Subpart B after the standards were proposed. This section was remanded for a second round of notice and comment. There were, however, no rulings about §191.16 issued on technical grounds.

In August 1987, the Department of Justice petitioned the First Circuit Court to reinstate all of 40 CFR Part 191 except for §191.15 and §191.16, which were originally found defective. The Natural Resources Defense Council filed an opposing opinion. The Court then issued an Amended Decree that reinstated Subpart A, but continued the remand of Subpart B.

In 1992, the WIPP LWA reinstated Subpart B of 40 CFR Part 191, except §191.15 and §191.16, and required the Administrator to issue final disposal standards no later than six months after enactment. On December 20, 1993, EPA issued amendments to 40 CFR Part 191 which eliminated §191.16 of the original rule; altered the individual-protection requirements; and added Subpart C on ground water protection (EPA93).

The revised Part 191 standard finalized in 1993 retained the waste containment and assurance requirements in the original 1985 standard. However, an important change was made for the individual-protection requirements: the protection dose limit was recalculated according to the newer Committed Effective Dose Equivalent (CEDE) methodology. This approach gave a dose limit of 15 mrem/yr. This new methodology considers the weighted relative importance of organ doses and the accumulation of dose potential over time. The original dose limit of 25 mrem/yr in the old methodology is equivalent to the 15 mrem/yr limit in the new system.

The revised Part 191 standard finalized in 1993 also moved the guidance on the treatment of human intrusion into a new Appendix C dealing with implementation of the rule's numerical standards. This guidance was subsequently supplanted by recommendations from the National Academy of Sciences in its report on the technical bases for Yucca Mountain standards (NAS95; see discussion below). With regard to the ground water protection standards, the revised Part 191 rule retained the requirements for specific radionuclides that were in the 1985 standards, but the compliance period was changed from 1,000 to 10,000 years to be consistent with the individual-protection requirement.

The WIPP LWA also exempted Yucca Mountain from the generic disposal standards set forth under 40 CFR Part 191, Subpart B. Pursuant to specific provisions in the EnPA, EPA was charged with setting site-specific environmental radiation protection standards for Yucca Mountain. The 40 CFR Part 197 standard is responsive to this mandate.

1.6 The National Academy of Sciences' Recommendations

In the EnPA, the Congress directed the Academy to address three issues in particular:

- *Whether a health-based standard based upon doses to individual members of the public from releases to the accessible environment will provide a reasonable standard for protection of the health and safety of the general public;*

- *Whether it is reasonable to assume that a system for post-closure oversight of the repository can be developed, based upon active institutional controls, that will prevent an unreasonable risk of breaching the repository's engineered or geologic barriers or increasing exposure of individual members of the public to radiation beyond allowable limits; and*

- *Whether it will be possible to make scientifically supportable predictions of the probability that the repository's engineered or geologic barriers will be breached as a result of human intrusion over a period of 10,000 years* (EnP92).

The NAS recommendations in these three areas had direct bearing on the approach used by EPA in developing its site-specific IPS, HIS, and GWS for Yucca Mountain.

To address these questions, the Academy assembled a committee of 15 members representing a range of scientific expertise and perspectives. The committee conducted a series of five technical meetings at which more than 50 nationally and internationally known scientists and engineers were invited to participate. In addition, the committee received information from the Nuclear Regulatory Commission (NRC), the Department of Energy (DOE), EPA, Nevada State and county agencies, and private organizations, such as the Electric Power Research Institute.

The committee's conclusions and recommendations are contained in its final report, entitled *Technical Bases for Yucca Mountain Standards*, which was issued on August 1, 1995 (NAS95). In this report, the committee offered the Agency several general recommendations as to the approach EPA should take in developing 40 CFR Part 197. Specifically, the NAS recommended (NAS95, p.2):

- *The use of a standard that sets a limit on the risk to individuals of adverse health effects from releases from the repository. 40 CFR Part 191 contains an individual-dose standard, and it continues to rely on a containment requirement that limits the releases of radionuclides to the accessible environment. The stated goal of the containment requirement was to limit the number of health effects to the global population to 1,000 incremental fatalities over 10,000 years. We do not recommend that a release limit be adopted.*

- *That compliance with the standard be measured at the time of peak risk, whenever it occurs. (Within the limits imposed by the long-term stability of the geologic environment, which is on the order of one million years.) The standard in 40 CFR Part 191 applies for a period of 10,000 years. Based on performance assessment calculations provided to us, it appears that peak risks might occur tens or hundreds of thousands of years or even farther into the future.*

- *Against a risk-based calculation of the adverse effect of human intrusion into the repository. Under 40 CFR Part 191, an assessment must be made of the frequency and consequences of human intrusion for purposes of demonstrating compliance with containment requirements. In contrast, we conclude that it is not possible to assess the frequency of intrusion far into the future. We do recommend that the consequences of an intrusion be calculated to assess the resilience of the repository to intrusion.*

The NAS committee also recommended that policy issues be resolved through a rulemaking process that allows opportunity for wide-ranging input from all interested parties (NAS95).

The committee also addressed each of the specific questions posed to it by the Congress in the EnPA. With regard to the first issue, protecting human health, the NAS committee recommended (NAS95, pp. 4-7):

- *...the use of a standard that sets a limit on the risk to individuals of adverse health effects from releases from the repository.*

- *...the critical-group approach be used in the Yucca Mountain standards.*

- *...compliance assessment be conducted for the time when the greatest risk occurs, within the limits imposed by long-term stability of the geologic environment.*

The NAS also concluded that an individual-risk standard would protect public health, given the particular characteristics of the site, provided that policy makers and the public are prepared to accept that very low radiation doses pose a negligibly small risk. A necessarily important component in the development of a standard for Yucca Mountain is the means of assessing compliance. The NAS committee concluded as follows (NAS95, p. 9):

- *...physical and geologic processes are sufficiently quantifiable and the related uncertainties sufficiently boundable that the performance can be assessed over time frames during which the geologic system is relatively stable or varies in a boundable manner. The geologic record suggests that this time frame is on the order of* 10^6 *years. The Committee further concluded that the probabilities and consequences of modifications by climate change, seismic activity, and volcanic eruptions at Yucca Mountain are sufficiently boundable that these factors can be included in performance assessments that extend over this time frame.*

- *...it is not possible to predict on the basis of scientific analyses the societal factors required for an exposure scenario. Specifying exposure scenarios therefore requires a policy decision that is appropriately made in a rulemaking process conducted by EPA.*

With respect to the second and third questions posed by the Congress in Section 801 of the EnPA, the NAS Committee concluded (NAS95, p. 11):

- *...it is not reasonable to assume that a system for post-closure oversight of the repository can be developed, based on active institutional controls, that will prevent an unreasonable risk of breaching the repository's engineered barriers or increasing the exposure to individual members of the public to radiation beyond allowable limits.*

- *...it is not possible to make scientifically supportable predictions of the probability that a repository's engineered or geologic barriers will be breached as a result of human intrusion over a period of 10,000 years.*

1.7 Final 40 CFR Part 197 - Public Health and Environmental Radiation Protection Standards for Yucca Mountain, Nevada

Three key elements of the 40 CFR Part 197 standard are the individual-protection standard (§197.20), the human-intrusion standard (§197.25), and the ground water protection standards (§197.30). These are discussed below and compared with the 40 CFR 191 generic disposal standards and the NAS recommendations. The basis for certain site-specific aspects of the regulation are also presented.

In developing a site-specific standard for the Yucca Mountain site, the generic requirements in Part 191 serve as a starting point for the process. The generic requirements in Part 191 were examined in terms of whether their components are relevant to the Yucca Mountain geologic setting; if they are determined to be relevant, the next issue is how they can be framed appropriately for that setting.

In contrast to the individual, human intrusion, and ground water protection standards, Part 191 also contained a containment requirement that was not carried into the Yucca Mountain standard. The containment requirement in Part 191 was intended to address a situation where releases from a poorly performing geologic repository could enter into large surface water bodies, such as rivers, lakes, or the ocean, where the contamination would be greatly diluted and the dose distributed to a potentially large population. The containment requirement was intended to limit such situations. For the Yucca Mountain setting, this scenario is not plausible since no large surface water bodies exist in the arid desert environment in the site vicinity. The text below discusses how the individual, human intrusion, and ground water protection standards were framed for the Yucca Mountain setting.

1.7.1 Individual-Protection Standard

An individual-protection standard is a relevant and fundamental regulatory requirement for any repository setting and therefore must be incorporated into any site-specific standard.

The individual-protection standard in Part 197 requires DOE to demonstrate:

> *...using performance assessment, that there is a reasonable expectation that for 10,000 years following disposal, the reasonably maximally exposed individual receives no more than an annual committed dose equivalent of 150 microsieverts (15 millirems) from releases from the undisturbed Yucca Mountain disposal system. The DOE's analysis must include all potential pathways of radionuclide transport and exposure* (EPA01).

By way of comparison, the individual-protection standard in the 40 CFR Part 191 generic disposal standard also specifies, at §191.15, an annual committed effective dose equivalent (CEDE) of 15 mrem. The use of an individual-protection standard rather than a release limit is consistent with recommendations of the NAS as discussed in 1.3 above. Further, the NAS noted that a risk range of 10^{-5} to 10^{-6} per year was a reasonable starting point for EPA's rule making (NAS95, p. 5). Thus selection of a CEDE of 15 mrem for 40 CFR Part 197, which is equivalent to an annual risk of $7x10^{-6}$, is also consistent with the NAS recommendations.

Total release limits in the generic Part 191 regulation were developed to protect the general population from repository releases via all pathways. The NAS concluded that protecting public health by establishing an individual-protection exposure limit is also an adequate means of assuring the general population is protected. For the Yucca Mountain site, the overwhelmingly dominant exposure pathway involves releases into the ground water system beneath the repository, followed by transport of contaminants to downgradient individual receptors. An all-pathways standard for an individual would therefore include the most important exposure pathways.

1.7.2 Human-Intrusion Standard

Inadvertent intrusion is an unanticipated event that could have consequences ranging from minor to highly significant depending on the geologic setting. An HIS was included in the generic Part 191 standard because of this potential range of consequences, and to enable the consequences to be examined for any specific repository site. For the Yucca Mountain setting, site characterization work has shown that potable water is the only recognized potential resource at and near the repository location. Recognizing the relatively low probability of intrusion into the repository for resource exploration, the NAS recommended that human intrusion be considered only as a stylized test of repository resiliency, separate and distinct from the evaluations of expected repository performance. The NAS did not find that consideration of human intrusion was inappropriate for the Yucca Mountain site. It made recommendations on framing the stylized scenario which were the bases for EPA's standard.

As discussed in Section 1.3 above, the NAS Committee on the Technical Bases for Yucca Mountain Standards concluded that active institutional controls would not be a reliable long-term deterrent to human intrusion into a repository. Consistent with this finding, EPA proposed two alternative approaches for consideration as the human-intrusion standard under 40 CFR Part 197. Under Alternative 1 for proposed §197.25, DOE would be required to demonstrate that:

> *...there is a reasonable expectation that for 10,000 years following disposal the reasonably maximally exposed individual receives no more than an annual committed effective dose equivalent of 150 microsieverts (15 mrem) as a result of human intrusion. The DOE's analysis of human intrusion must include all potential environmental pathways of radionuclide transport and exposure* (EPA99).

Under this alternative NRC would determine the range of time during which intrusion occurs based on EPA guidance provided in proposed §197.26.

Under Alternative 2 the DOE would be required to determine:

> *...the earliest time after disposal that the waste would degrade sufficiently that a human intrusion ... could occur without recognition by the drillers* (EPA99).

In the final rule, EPA selected this second alternative in which DOE must project the time at which waste packages have degraded sufficiently that penetration of a waste package by a drilling intrusion could occur without being noticed by the drillers. A connection between the repository and the underlying saturated zone below the repository is established by the intruding borehole penetration, and doses from the single breached waste package are to be projected in the same manner as for the individual-protection standard compliance calculations. The same dose limit is applied, as used for the individual-protection standard, but the calculation is a separate performance scenario independently calculated and evaluated against the 15 millirem/yr limit. If exposures occur before the end of the regulatory period, the calculations assessments are evaluated against the 15 millirem/yr limit. If exposures occur after the regulatory period, the assessments are included in the repository Environmental Impact Statement.

In each case a single vertical borehole is assumed to penetrate the degraded waste package and continue down to the saturated zone. Similar to 40 CFR Part 191, intrusion is limited to inadvertent exploratory drilling for resources. However, the frequency of intrusion is different in the two regulations. The Appendix C Guidance to the generic disposal standards specifies that the drilling not exceed 30 boreholes per square kilometer per 10,000 years for repositories near sedimentary rocks and 3 boreholes per square kilometer per 10,000 years for repositories in other geologic formations. This Appendix C Guidance was refined for the Waste Isolation Pilot Plant in 40 CFR Part 194 (Criteria for the Certification and Re-Certification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations). In §194.33 drilling frequency is based on the frequency of drilling for resources for the past 100 years within a particular geographic area (i.e., the Delaware Basin) surrounding the WIPP Site. This requirement is appropriate for an area where extensive drilling for a variety of resources had occurred. Since the Yucca Mountain area has not been subject to extensive exploration drilling, the Agency chose the approach very similar to that recommended by the NAS, namely a "stylized intrusion scenario consisting of one borehole of a specified diameter drilled from the surface through a canister of waste to the underlying aquifer" (NAS95, p. 111).

1.7.3 Ground Water Protection Standards

Ground water protection standards were included in the generic Part 191 standards and in the WIPP certification effort. Inclusion of ground water protection standards in the Yucca Mountain standard can be considered relevant for several reasons. The repository site is located in the unsaturated zone (UZ) directly above potable water sources; any contaminant releases into the UZ will move downward into these aquifers, which supply water to the population downgradient of the site. Also, protection of ground waters is well-established national policy. From a purely technical perspective, the NAS chose not to consider the question of ground water standards, noting that an all-pathways exposure limit would include doses from ground water use. However, it is Agency policy, as well as national policy, and the policy of most states, to protect ground water resources.

Throughout the NAS report the text acknowledged that EPA may elect to take approaches other than a narrow interpretation of the committee's recommendations for reasons other than specified in the report. In this way, the broader role of the Agency in applying policy factors as well as technical rationale was acknowledged.

The Safe Drinking Water Act (SDWA) was enacted to assure safe drinking water supplies and to protect against endangerment of underground sources of drinking waters (USDWs). Under the authority of the SDWA, the EPA issued interim regulations (40 CFR Part 141, Subpart B) covering the permissible levels of radium, gross alpha, man-made beta, and photon-emitting contaminants in community water supply systems (EPA76). Similar to hazardous chemical substances, limits for radionuclides in drinking water are expressed as Maximum Contaminant Levels (MCLs). The current MCL for radium-226 and radium-228 combined is 5 pCi/l, and the MCL for gross alpha particle activity (including radium-226, but excluding radon and uranium).

is 15 pCi/l. For man-made beta particle- and photon-emitting radionuclides (except tritium and strontium-90), individually or in combination, the MCL is set at an annual dose limit of 4 mrem to the total body or any internal organ. For tritium and strontium-90, the MCLs are 20,000 pCi/l and 8 pCi/l, respectively.

In 1991, the EPA issued a Notice of Proposed Rulemaking (NPRM) under 40 CFR Parts 141 and 142 to update the 1976 interim regulations for radionuclide water pollution control (EPA91). The NPRM, under the SDWA, proposed the establishment of Maximum Contaminant Level Goals (MCLGs) and Maximum Contaminant Levels (MCLs). The MCLGs and MCLs target radium-226, radium-228, natural uranium, radon, gross alpha, gross beta, and photon emitters. As proposed, MCLGs are not enforceable health goals. In contrast, MCLs are enforceable standards. The EPA concluded that radionuclide MCLGs should be set at zero to avert known or anticipated adverse health effects while providing an adequate margin of safety. In setting the MCLs, the EPA also committed itself to evaluating the feasibility, costs, and availability of water treatment technologies, as well as other practical considerations. The 1991 proposed rulemaking included the following MCLs: radium-226, 20 pCi/l; radium-228, 20 pCi/l; radon-222, 300 pCi/l; uranium, 20 micro g/l; adjusted gross alpha, 15 pCi/l; and beta and photon emitters, 4 mrem ede/yr.

The generic disposal standards at 40 CFR Part 191 also incorporate the 40 CFR 141 Subpart B ground water protection requirements. EPA believes that it is prudent and appropriate to impose requirements for waste disposal that are protective of water resources for future generations, without imposing a burden of water treatment and cleanup on those future generations.

In the Yucca Mountain standard, DOE is required under §197.30 to provide, in its license application to NRC:

> *...a reasonable expectation that, for 10,000 years of undisturbed performance after disposal, releases of radionuclides from waste in the Yucca Mountain disposal system into the accessible environment will not cause the level of radioactivity in the representative volume of ground water to exceed the limits in Table 1...(EPA01).*

Table 1 limits combined Ra-226 and Ra-228 to five picocuries per liter (pCi/l) including natural background and gross alpha activity (including Ra-226 but excluding radon and uranium) to 15 pCi/l including natural background. Combined beta and photon emitting radionuclides are limited to levels where the annual dose (excluding natural background) to the whole body or any organ will not exceed 40 microsieverts (4 mrem). These limits are the same as the maximum contaminant levels (MCLs) established by the Agency under the Safe Drinking Water Act (SWDA).

1.7.4 Site-Specific Regulatory Requirements

While many elements of the 40 CFR Part 197 rule are either similar to other EPA regulations such as 40 CFR 191 and 40 CFR Part 141 or based on recommendations of the NAS, certain elements are based on site-specific considerations. These include the definition of the reasonably maximally exposed individual (RMEI), the location of the point of compliance, and the representative volume of water for measuring compliance with the ground water protection standard. Each of these site-specific elements are discussed below.

***Reasonably Maximally Exposed Individual** (RMEI)*

For DOE to determine whether the Yucca Mountain disposal system complies with the individual-protection standard, they must calculate the dose to an individual or group of individuals and compare that dose with the requirements contained in §197.20 (i.e., a maximum annual CEDE of 15 mrem). The regulation must specify those characteristics, habits, age, life-style, etc. which describe the individual or group of individuals. For this purpose EPA has chosen to use, as the basis for comparison with the individual-protection standard, the dose received by the reasonably maximally exposed individual.

The RMEI is defined in §197.21 as a hypothetical person who:

> *(a) lives in the accessible environment above the highest concentration of radionuclides in the plume of contamination;*
> *(b) Has a diet and living style representative of the people who now reside in the Town of Amargosa Valley, Nevada. The DOE must use projections based upon surveys of the people residing in the Town of Amargosa Valley, Nevada, to determine their current diets and living styles and use the mean values of these factors in the assessments conducted for §§ 197.20 and 197.25; and*
> *(c) Drinks two liters of water per day from wells drilled into the ground water at the location [where the RMEI lives].* (EPA01)

The NAS recommended that the risk to the average member of the critical group be used as the basis of comparison with the risk limit of the standard. The NAS Committee proposed two alternatives – a probabilistic critical group approach and a subsistence farmer critical group. After considering these possibilities, the Agency decided to use the RMEI concept which is consistent with other EPA programs and is believed by the Agency to provide a level of protection substantially equivalent to that provided by the critical group concept for small populations. The RMEI concept involves estimating high-end doses which are in excess of the 90th percentile of the range of doses for the exposed population. The goal is to calculate doses which are not the most extreme but are well above the average for the exposed population.

EPA considered four possible scenarios to define the RMEI including (EPA99):

- A subsistence farmer residing 30 to 40 km downgradient at a location where the water table is near the surface, who obtains all food and water from contaminated sources

- A commercial farmer subject to the same exposure pathways as the subsistence farmer.

- A community located near the repository site that obtains its water for domestic use from an underground source of drinking water.

- A rural-residential RMEI exposed to the same pathways as the subsistence farmer. However, the rural-residential RMEI does personal gardening but does not work as a full-time farmer.

The fourth scenario was chosen as the basis for developing the specific requirements under §197.21. This scenario is believed to be representative of most of the current residents of the Amargosa Valley.

Representative Volume of Ground Water

In accord with Agency policy of protecting ground water resources, the Representative Volume (RV) concept was developed in response to consideration of the actual resource to be protected at the site. The RV is based on current land uses involving ground water, i.e , the resource to be protected, and the fundamental assumption is that future lifestyles and water uses will be the same as those of the present. This assumption is necessary to avoid making judgments based on speculation. The RV is intended to be a volume of water used annually that provides the basis for calculating radionuclide concentrations resulting from repository releases. Resulting concentrations would be compared to MCLs established in the SDWA.

The representative volume is the volume of water needed to supply the demands of a defined RMEI that could exist in the future at the point of compliance for the ground water protection standards (see discussion below for details on point of compliance). To meet such demands, the water must contain less than 10,000 milligrams of total dissolved solids per liter (i.e., potable).

The proposed Part 197 standards included a number of possible RVs based on current land uses south of Yucca Mountain. One proposed alternative was 1,285 acre-feet/yr. This RV is the sum of the water requirements for alfalfa farming and domestic use. It is based on a small farming community of 25 people with 255 acres of alfalfa under cultivation (the average current size of these farms in the area) which is the current economic base for the Amargosa Valley. Alfalfa farming requires about 5 acre-feet of water per acre (255 acres x 5 acre-feet per acre = 1,275 acre-feet for irrigation). The average annual water demand for a non-farming family of four with a garden is 10 acre-feet. This is also the lower bound for the amount of water used through 15 connections from public water supply serving at least 25 people (as defined in the SWDA). The representative volume is, therefore, the sum of the water requirements for alfalfa farming and domestic use.

Another alternative RV proposed was 120 acre-feet/yr. This value corresponds to the water use for a small municipal community of approximately 150 individuals who use the water for domestic and municipal purposes.

For the final rule, a representative volume of 3,000 acre-ft/yr was defined. This representative volume, as described in the preamble to the final rule (66 FR 32074-32135, June 13, 2001), represents a composite of the water demands for downgradient users of the ground water resource. The composite water use estimate includes current use for alfalfa cultivation (the largest consumer of water for agricultural purposes), and projected increases for population and commercial/industrial uses in the Lathrop Wells area northward to the boundary of the Nevada Test Site.

Section 197.31 describes the RV and includes specific concepts concerning how the RV could be incorporated into the radionuclide transport modeling that will be included in analyses to support demonstration of compliance during the licensing process.

Point of Compliance

In the proposed rule, two mechanisms were proposed for compliance determinations, specifically to identify where ground-water contamination and individual radiation exposures are to be projected for comparison against the limits contained in the standard. One alternative was a controlled area concept, similar in intent to the concept as originally used in Part 191. The controlled area denotes a bounded geographic area within which the standards would not be applied. The standard's limits would be applied at the boundary of the controlled area, which serves as the beginning of the defined "accessible environment." The land within the boundary of the controlled area is considered part of the natural barrier of the disposal system, and as such is dedicated to the sole purpose of isolating the radioactive wastes from the accessible environment. The second proposed alternative was the use of a compliance point, which serves the same purpose as the border of the controlled area - it identifies the point at which ground water contaminant concentrations and individual exposures are calculated for comparison against the standard's limits. The point of compliance is to be located at a specific distance from the repository and over the point at which calculated releases from the repository are projected to be at their highest levels in the ground water beneath this point.

In the proposed rule EPA included four compliance measure alternatives for consideration, two of which incorporated a controlled area and two of which incorporated a compliance point. These alternatives include downgradient distances of 5, 18, 20, and 30 km. At the present time there is no one residing 5 km downgradient[****] from the repository, since it is within the boundaries of the Nevada Test Site (NTS); there are about 10 people residing between 18 km (the NTS boundary) and 20 km downgradient, and hundreds of persons around 30 km downgradient. Future population increases are expected at the 20- and 30-km downgradient locations (EPA99, 01). In addition, the depth to ground water decreases from about 300 meters near the repository location to about 50 to15 meters within that portion of the Town of Amargosa Valley where most of the population resides and commercial agriculture is the basis for the local economy.

In the final rule, the Agency has incorporated a controlled area concept as a compliance mechanism, as defined in Section 197.12 of the final rule. The controlled area concept comports more directly with the direction of the EnPA, which explicitly mentions the "accessible environment" and refers to its definition from Part 191 which incorporates the controlled area concept. The controlled area concept also more clearly delineates the extent of the natural barrier around the repository than the simpler point of compliance approach. Neither the point of compliance, nor the controlled area approach imposes any significant cost impacts on the repository development program, because the site characterization efforts to define the magnitude and direction of potential releases are the same for either approach.

[****] This is the same compliance point as specified in 40 CFR Part 191, the generic disposal standard.

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2.0 OVERVIEW OF RADIOACTIVE WASTE DISPOSAL AT YUCCA MOUNTAIN

This chapter briefly describes the Yucca Mountain site and the wastes that would be stored and disposed there if the site is approved for disposal. A summary of current estimates of repository program costs, which total approximately $57.6 billion, is included.

2.1 Yucca Mountain as a Disposal Site

The Nuclear Waste Policy Amendments Act of 1987 (which amended the Nuclear Waste Policy Act (NWPA) of 1982) designated the Yucca Mountain site in Nevada as the only location to be evaluated as a possible place for disposal of spent nuclear fuel and high-level radioactive wastes. The Yucca Mountain site is located about 90 miles north of Las Vegas, Nevada, and is situated on the boundary of the Nevada Test Site. The climate is semi-arid, and the location was originally selected as a candidate location for disposal because it was expected that there would be limited potential for water to enter the repository and then to transport radionuclides to distant locations.

2.2 Sources and Characteristics of Radioactive Wastes to Be Disposed

A repository at Yucca Mountain would dispose of spent fuel from nuclear power reactors and high-level wastes from reprocessing of spent fuel. The sources of spent fuel would be commercial nuclear power reactors, naval reactors, and reactors used in DOE and research programs. High-level wastes are the result of defense operations in the states of Washington, Idaho, and South Carolina where fuel from production reactors was processed to obtain the uranium and plutonium used in nuclear weapons. They will consist of solidified fission product waste separated from the recovered uranium and plutonium.

The NWPA limited the amount of wastes to be disposed at Yucca Mountain to 70,000 metric tons equivalent of uranium (MTU). The DOE has interpreted this to correspond to disposal of 63,000 metric tonnes of spent fuel and the equivalent of 7,000 MTU of high-level wastes. The 70,000 MTU limit remains in force today, but is subject to change by future Congressional action.

The wastes would come to Yucca Mountain for disposal from commercial nuclear power sites and DOE operations sites throughout the country, as shown in Figure 2-1. At present, the spent fuel from commercial power reactors is primarily stored at the sites where the fuel was used in the reactors. The amount currently in storage totals about 40,000 MTU. Such spent fuel continues to be discharged from the commercial reactors at a total annual rate of about 2,200 MTU. If all

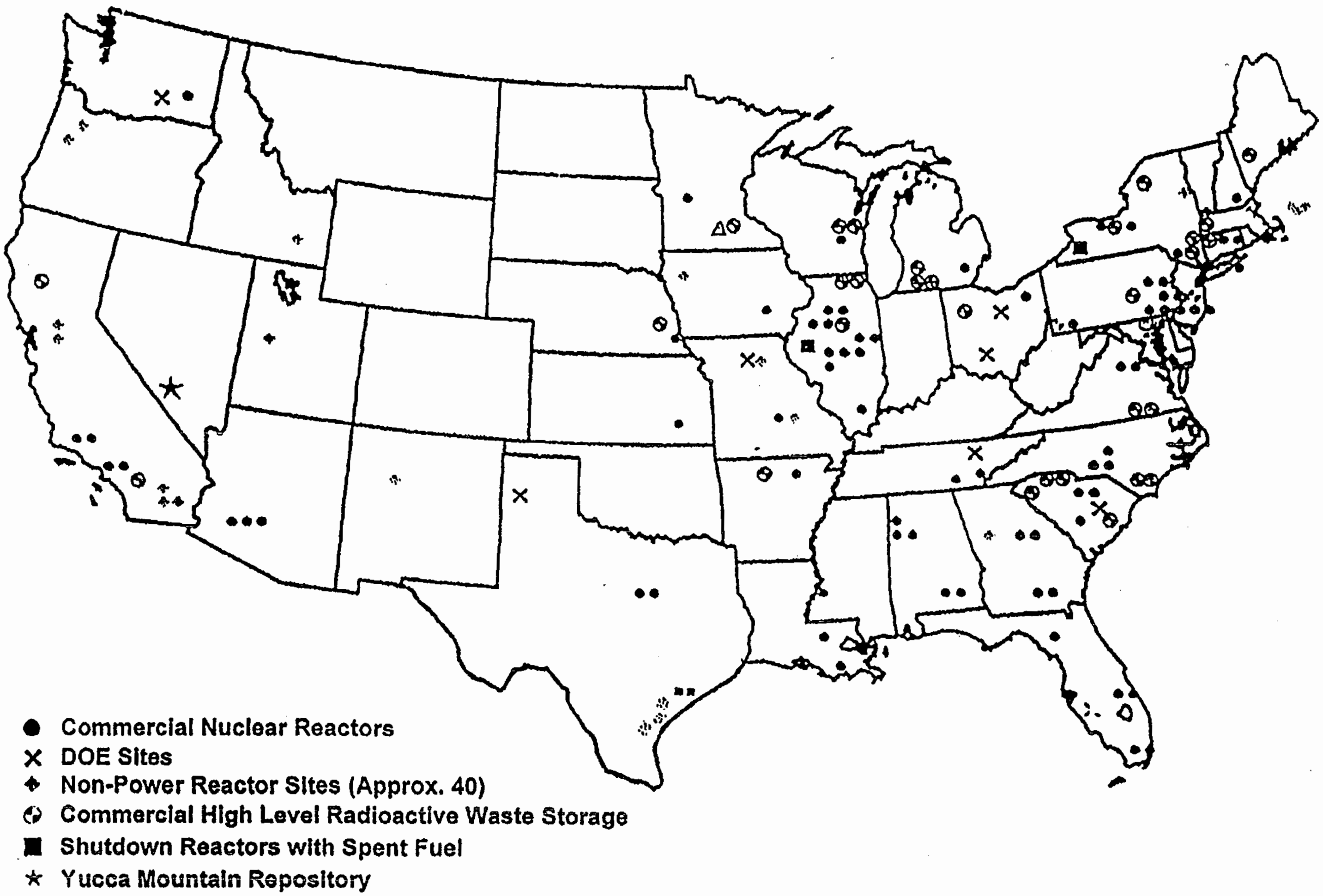


Figure 2-1. Sources of Radioactive Wastes for the Yucca Mountain Repository

reactors operate to the end of their current licenses, the total amount of spent nuclear fuel discharged will be about 87,000 MTU.

The DOE spent fuel, which comes primarily from research and test reactors, and spent fuel from naval nuclear reactors, is presently stored at various DOE sites. The current total amount of this spent fuel is less than 3,000 MTU, and the amount will not increase significantly.

High-level wastes were generated by defense production operations at DOE's Savannah River, Idaho, and Hanford, Washington sites. In the as-generated form, these wastes are liquid and have a total amount of tens of millions of gallons. The wastes will be solidified, and the amount sent to Yucca Mountain, in terms of number of cans of waste to be disposed, will depend on the solidification process used. The draft Environmental Impact Statement for the proposed repository at Yucca Mountain, issued by DOE in August 1999, estimated that the 7,000 MTU of HLW would be contained in about 14,000 waste canisters (DOE99).

2.3 Overview of the Repository for Disposal

The basic concepts for disposal of highly radioactive wastes into geological formations were set forth by the National Academy of Sciences in the 1950's and have been embodied in repository design concepts and regulatory concepts ever since then. The wastes are to be emplaced in deep geological formations which isolate them from the human environment, and a system of engineered and natural barriers is to be used in combination to maintain the wastes in isolation and to prevent release of radionuclides. The Yucca Mountain site, and other sites that had been under consideration, would use a combination of engineered and natural barriers appropriate to the site to maintain the wastes in isolation and to demonstrate compliance with regulatory standards for radionulides that were released from the repository.

At Yucca Mountain, the repository would be excavated in the unsaturated zone, i.e., in a geologic formation in which the pores and fractures in the geologic medium are not filled with water. The Yucca Mountain site, in comparison with other candidate sites, was unique in having capability for this type of emplacement. It was expected that the lack of ability for water to reach the wastes and transport them to the environment would dominate the safety performance of the repository and enable easy demonstration of compliance with regulatory standards.

2.4 DOE Estimate of the Repository Program Cost

DOE documented estimated repository program costs in the Viability Assessment (VA) documents (DOE98). The principal cost elements were identified as follows:

Historical costs -	$ 5.9B
Costs to complete work to the License Application-	1.1B
Respository costs from licensing to closure -	18.7B
Total for the repository program -	$25.7B

Estimates of costs for design options (options to the VA design) were provided in Volume 5 of the VA document. One of the options considered was use of drip shields and backfill, as is now planned for the current design, EDA II (see Section 3.6). The estimated cost of this option was $0.8 billion. However, this estimate did not consider the long-term total cost of these modifications.

DOE has released an updated "Total System Life Cycle Cost" (TSLCC) estimate (DOE01a), which gives a total cost for the repository of $57.6 billion, which includes historic costs. This higher cost includes cost elements not included in the VA estimate, and is a more accurate estimate of total program costs.

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 repository system 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.

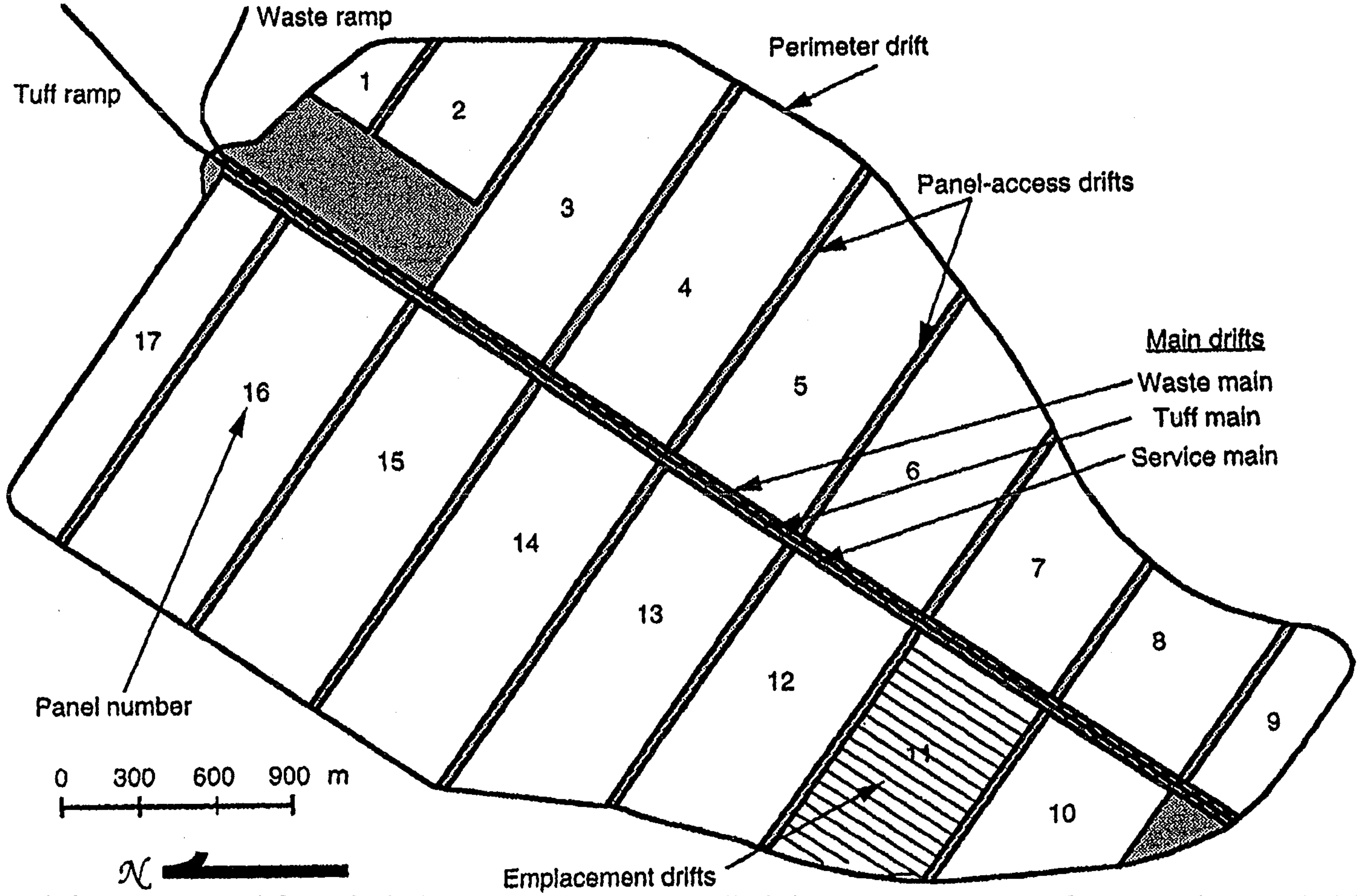


Figure 3-1. Layout of the Site Characterization Plan Repository

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

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 5^{th} and 95^{th} 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 mrem/yr.</u>, 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.

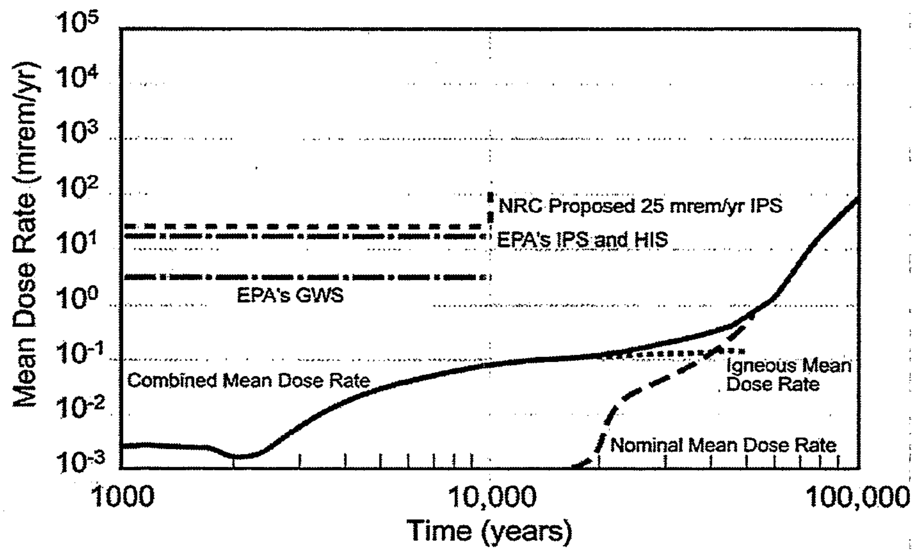


Figure 3-2. Comparison of Radiation Protection Standards with Expected Values of TSPA-SR Calculations for a Repository at Yucca Mountain for Nominal and Igneous Scenarios (Figure adapted from TRW00a)

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

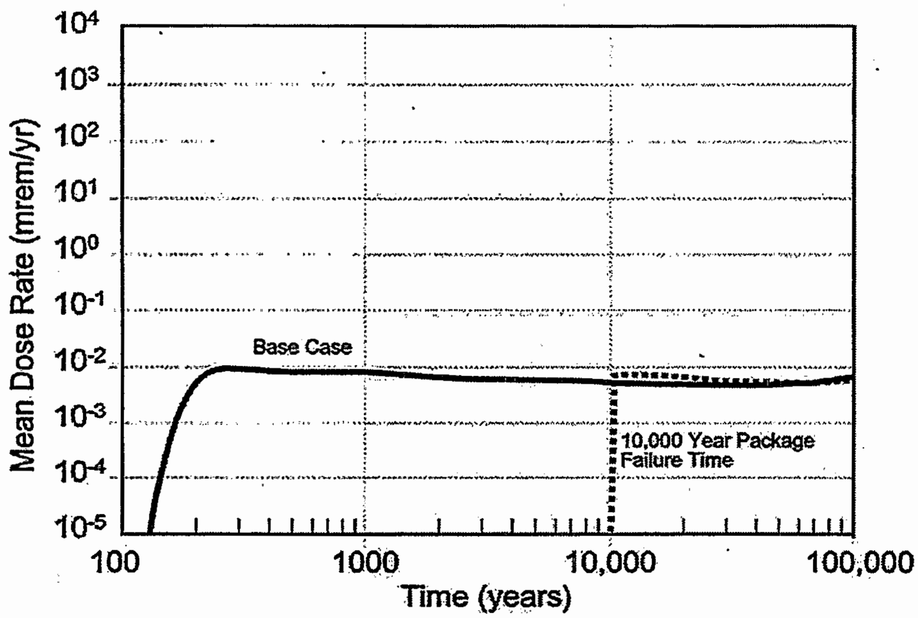


Figure 3-3. Expected Values of TSPA-SR Calculations for a Repository at Yucca Mountain for the Inadvertent Human Intrusion Scenario (Figure adapted from TRW00a)

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.

4.0 EVOLUTION OF PERFORMANCE ASSESSMENT AND BARRIER ROLES

This chapter summarizes and evaluates the repository system performance assessments that have been conducted by the Yucca Mountain program. Results of recent performance assessments demonstrate that the current repository design is able to meet, by a large margin, a 15 mrem CEDE individual-protection standard and the ground water protection and human-intrusion standards.

This section presents and discusses performance assessment results that have been conducted by DOE for Yucca Mountain. It also discusses conservatism in the models and assumptions that led to the assessment results, and alternative results that might be obtained through selection of alternative dose receptors or repository designs. The sub-sections of this chapter examine DOE's performance assessments to date and the use of conservatism in the definition of the performance scenarios and their analysis.

There will always be uncertainties inherent in modeling the interaction of the natural and engineered components of the repository system over the long time frames involved in projecting the repository's performance, and the performance projections are always subject to these uncertainties. Uncertainties should not always be assumed to mean the repository performance will be worse than quantitative estimates indicate, but it is always desirable to reduce uncertainties to the extent possible and practical. To reduce uncertainties, the DOE repository effort could elect to enhance the repository engineered components to reduce or eliminate the potential effects of the uncertainties, or expend additional effort to characterize and model the interaction between the natural and engineered systems more realistically to remove overly conservative assumptions used in prior assessments. The results of the assessments described here indicate that the repository design evolution was not driven by the components of the EPA standard, but rather by the uncertainties in the interaction of the natural and engineered systems at the repository site, as well as the very conservative approach taken in framing the performance scenarios in the DOE performance assessments.

4.1 Performance in Comparison with the Individual-Protection Standard

The TSPA-SR included a comprehensive TSPA effort, and was intended to be a complete demonstration of the ability of the system to meet proposed technical requirements. The TSPA-SR performance evaluations used a complex system of linked computer codes to model the performance factors; and used a suite of highly conservative assumptions concerning performance of the engineered features of the repository as the basis for the performance models. Most notably, the TSPA-SR assumed violent disruption of the repository by strombolian igneous intrusion, leading to complete destruction of waste packages contacted by the magma. As discussed in Section 3.7, both the existence of strombolian activity at Yucca Mountain and the subsequent behavior of the magma in contact with waste packages are questionable, and are likely to be extremely conservative. Modification of any of the key assumptions associated with the igneous scenarios would likely lead to negligible releases from the repository in the 10,000-year performance period.

The TSPA-SR represents the latest step in an evolution of the TSPA of Yucca Mountain. The earlier TSPA-VA methodology and assumptions were used to produce the performance assessment results presented in the DEIS for a repository at Yucca Mountain (DOE99). A key point is that the TSPA-VA analyses of the anticipated conditions (nominal scenario) were generally more conservative than those in the TSPA-SR. Despite this additional conservatism, the TSPA-VA was able to meet all applicable standards for Yucca Mountain. Consequently, TSPA-VA results for the nominal scenario continue to be relevant as a conservatively biased representation of Yucca Mountain performance relative to current understanding and the current EDA II design. Furthermore, this means that conclusions made in the DEIS regarding the ability of Yucca Mountain to meet performance objectives are still correct and appropriate.

Minor modifications to the TSPA-VA models were made for the DEIS evaluations in order to accommodate the DEIS options that were considered (e.g., alternative areal mass loadings and alternative waste quantities disposed), but the intent for the DEIS performance evaluations was to use the same basis used for the TSPA-VA evaluations. The DEIS included estimates of radionuclide concentrations in ground water that can be compared with EPA's ground water protection standards, discussed in Section 4.2.

The uncertainties in performance of the EDA II repository are also significantly less than those for the VA repository; as previously discussed, and as illustrated in Table 3-5, the EDA II design features were selected specifically to reduce performance uncertainties as well as to improve the margin between expected performance and the regulatory standard.

In summary, it is evident that the expected performance in TSPA-SR is significantly better than that of the VA repository; this is the result of design features specifically selected to improve expected performance and to reduce uncertainties in expected performance. Furthermore, improved model rigor and supporting data have eliminated consideration of juvenile failure mechanisms that led to early releases in TSPA-VA. Currently, the only credible mechanisms for release from the repository in the performance period are associated with igneous activity. As discussed earlier, this scenario is treated with extreme conservatism. A more reasonable treatment of igneous activity would likely lead to negligible releases from this scenario.

The EPA individual-protection standard of 15 mrem/yr at 10,000 years and 18 km therefore is not controlling or forcing DOE's approach to repository design. As discussed in Section 3, the evolution of the repository design, performance assessment methodology, and performance assumptions has been driven by factors other than the EPA IPS standard.

4.2 Performance in Comparison with the Ground Water Protection Standards

In the DEIS for Yucca Mountain, DOE calculated and reported ground water concentrations of radionuclides released from a repository at Yucca Mountain. The evaluations used the VA design and modeling methods and were, therefore, as previously noted, highly conservative, i.e., they overstate the expected concentration by several orders of magnitude. Furthermore, they overstate expected concentrations with respect to the current EDA II design and the TSPA-SR results.

The results of the DEIS concentration evaluations for the radionuclides released during periods up to 10,000 years and transported to locations at 5, 20, and 30 km downstream from the repository are summarized and compared to the current (1976) Maximum Concentration Limits (MCLs) in Table 4-2. The DEIS concentration values are strongly influenced by the assumed juvenile waste package failure at 1,000 years and by assumptions of limited dilution during transport. As a result of the assumptions that maximize the amount of release from the repository and minimize dilution during transport, the radionuclide concentrations shown in Table 4-2 are much higher than would reasonably be expected with more realistic assumptions for the performance scenarios.

As can be seen in Table 4-2, the concentrations reported in the DEIS for the TSPA-VA repository are well below the current MCL values despite the conservative assumptions and design that are the basis for the performance calculations.

As shown above in Section 3.7, no radionuclide releases from the EDA II repository would be expected during 10,000 years unless it is violently disrupted by volcanic activity. The results for the EDA II design from the TSPA-SR for comparison with the ground water protection MCLs are shown in Figures 4-1 and 4-2. The ground-water protection analyses assumed a representative water volume of 1285 acre-feet/yr centered on the highest concentration in the plume in the saturated zone. It was recognized in the TSPA-SR (TRW00a) that the regulatory time period for ground-water protection is 10,000 years. However, the analyses were carried out

Table 4-1. Comparison of DEIS Ground Water Radionuclide Concentrations with MCLs

Radionuclide Contributors to 10K-Year Dose	Current (1976) MCL, in pCi/l	Mean Conc. for 85 MTU/acre*, 5 km 20 km 30 km	95th Percentile Conc. for 85 MTU/acre, 5 km 20 km 30 km	Mean Conc. for 25 MTU/acre, 5 km 20km 30 km	95th Percentile Conc. for 25 MTU/acre, 5 km 20 km 30 km
Tc-99	900	45 30 10	390 84 130**	17 7.3 4.5	1.9 14 6.3
I-129	1	0.13 0.07 0.04	0.57 0.12 0.20	0.10 0.50 0.02	0.40 0.15 0.0
C-14	2,000	2.1 1.1 0.64	8.2 1.8 3.1	1.6 0.79 0.40	5.6 5.9 0.21

* The 85 MTU/acre thermal loading is the VA design value. The DEIS Proposed Action corresponds to the VA design, but the DEIS also considered options of 60 and 25 MTU/acre.

** The apparent inversions of concentrations with distance are a consequence of the modeling methods used for the DEIS performance evaluations.

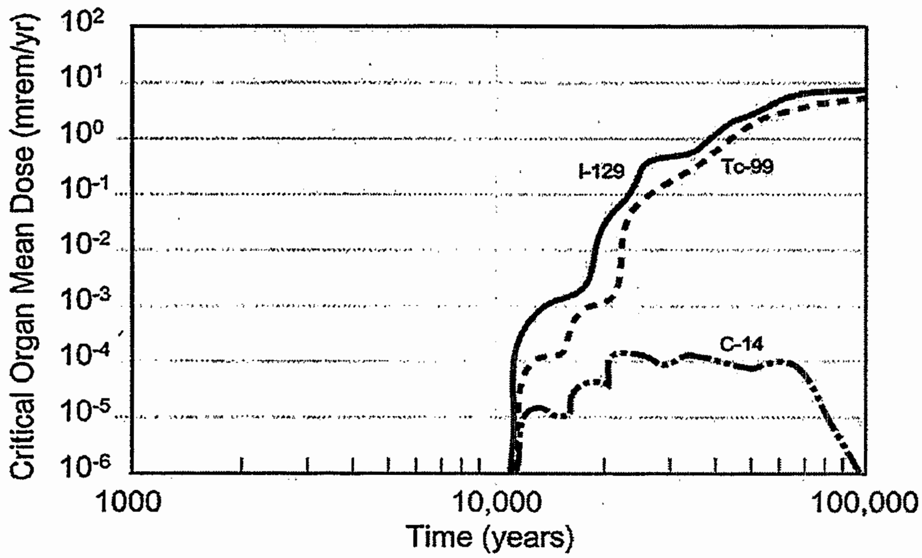


Figure 4-1. Summary of Groundwater Protection Performance Results of the TSPA-SR: Combined Beta and Photon-Emitting Radionuclides (Figure adapted from TRW00a)

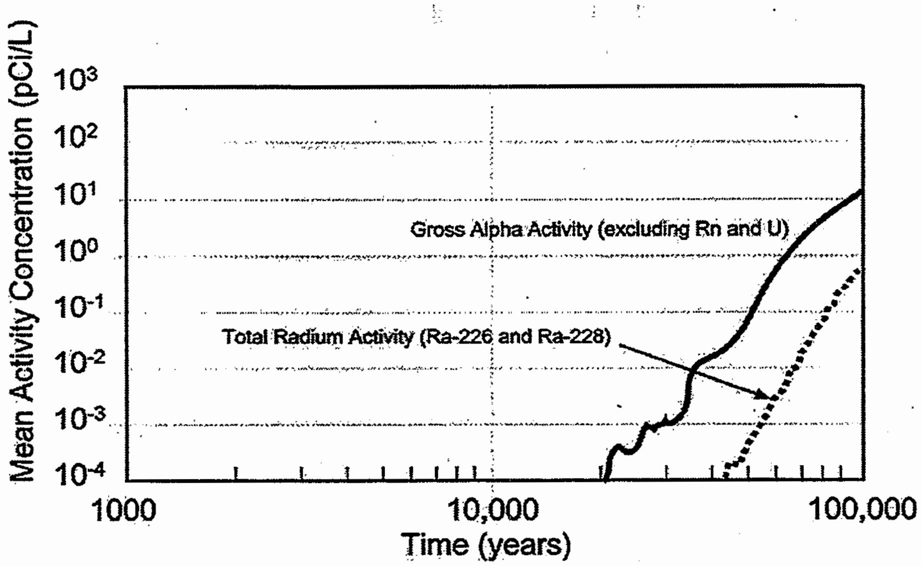


Figure 4-2. Summary of Ground-Water Protection Results for TSPA-SR for Gross Alpha Activity (Figure adapted from TRW00a)

to 100,000 years to ensure that no significant degradation of the performance occurs after 10,000 years.

The performance of the repository in the TSPA-SR is shown to be significantly improved compared to the performance presented in Table 4-2 for the TSPA-VA over 10,000 years. This dramatic improvement in calculated performance is the result of improved design and more credible treatment of the failure of waste packages.

Sequential analyses on several designs and using several TSPAs have been analyzed for comparison with current ground water MCLs. These have included comparisons in the DEIS, TSPA-VA, and TSPA-SR. In the TSPA-VA the MCLs were met by a substantial margin, despite significant levels of conservatism built into model assumptions, which would increase the compliance margin to orders of magnitude if more realistic scenario and model assumptions were used. In the DEIS, the MCLs were met despite even more conservatism applied to the analysis. In the TSPA-SR, ground-water concentrations are projected to be zero for the first 10,000 years. The current ground water protection MCLs therefore are not expected to affect the repository design or costs.

4.3 Conservatism in the TSPA-VA, TSPA-DEIS, AND TSPA-SR Evaluations

As previously noted, DOE exercised considerable conservatism in the modeling methods and assumptions for the TSPA-SR dose projections. These assumptions were more realistic and less conservative than the earlier TSPA-VA approaches for the nominal scenario, but still retain a significant conservative bias. Both TSPA-SR and TSPA-VA reports, and their supporting technical basis documents, provide a comprehensive description of the modeling methods and assumptions. The DEIS states that the TSPA-VA methods and assumptions were used to produce the TSPA-DEIS results, except for minor modifications to accommodate the waste inventory and thermal loading options considered in the DEIS but not considered in the VA. Since the TSPA-VA has been shown to be more conservative than the TSPA-SR for the nominal scenario, the results and conclusions of the DEIS remain appropriate.

The strategic approach used by DOE for TSPA-VA, TSPA-DEIS, and TSPA-SR modeling and assumptions can be summarized as follows:

- Values and distributions for natural system performance parameters such as water infiltration rates were as realistic as possible on the basis of data available at the time of the analyses. Uncertainties in these performance factors were so high that it would be difficult to identify and characterize conservatism for them; values for many of these parameters, such as dilution during transit of the saturated zone, were based, as necessary, on the results of expert elicitations.

- Biosphere dose-conversion factors were as realistic as possible on the basis of standard pathway parameters and local data on current human locations and activities such as farming.

- Some performance factors that could contribute significantly to deferral of radionuclide release from the repository, to reduction of release quantities, and to reduction of radionuclide concentrations in the biosphere were simply omitted from the performance model system if parameter values and distributions of values could not readily be established and defended. Such factors include dilution of radionuclide concentrations in water within a failed package, delays in radionuclide release from a failed package as a result of low water entry rates, and dilution of ground water concentrations at the dose receptor location as a result of pumping. Each of these factors will tend to either delay doses to later times, or to lower the peak dose.

- Conservatism was exercised for engineered barrier system performance parameters, for which a data and/or experience base exists and enables a characterization of conservatism. This implementation of conservatism is discussed below for specific performance factors: juvenile failures, crevice corrosion, water flow into the package interior, exposed waste form area, and in-package dilution and transport delays.

4.3.1 Assessment of Juvenile Failure

In the TSPA-VA, doses prior to 10,000 years were dominated by juvenile failures, specifically by the potential for weld failures associated with defects at emplacement despite rigorous inspection procedures. The potential for juvenile failures is inevitable, owing to the possibility for human errors in manufacturing, inspection, and emplacement. In the absence of such effects, the design basis lifetime for the waste package in the TSPA-VA was very long, and precluded releases during the first 10,000 years, with early corrosion failures limited to less than 20 waste packages out of a population of about 10,000 within 10,000 years (DOE98a, Volume 3, Figure 4-13). In the TSPA-VA, therefore, the potential for these problems was treated using a conservative screening approach. The subsequent results therefore constituted a real-world worst case scenario.

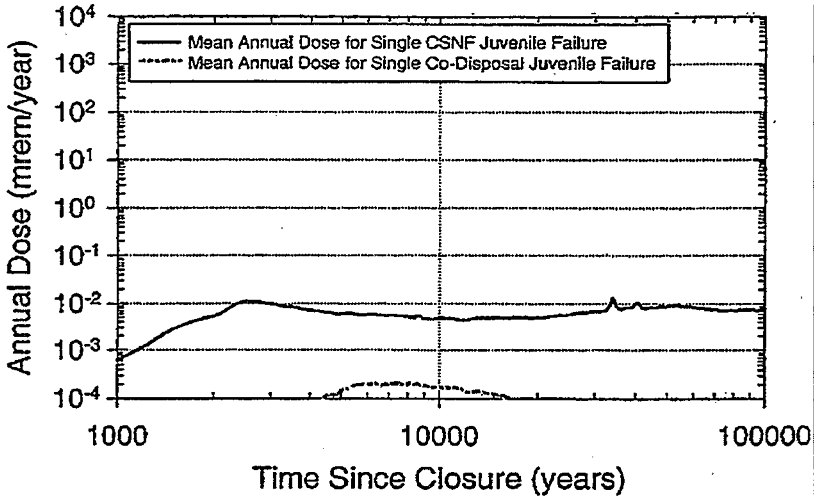


Figure 4-3. Estimates of the Consequence of an Artificial Juvenile Failure

Penetration of a single waste package was assumed in the TSPA-VA base case to occur at 1,000 years as the result of a phenomenon such as failure of a bad weld. The TSPA-VA assumed entry and exit holes form at the same time. Seepage was assumed to enter the package, since the entire waste package was assumed to be wetted. These assumptions provided essentially an instantaneous high release rate, which is an unrealistic and very conservative treatment of weld-failure effects. The penetration was assumed to result in immediate release of radioactivity from 1.25 percent of the cladding. This single package failure assumption contributed about 50 percent of the base-case 10,000-year dose rate of 0.04 mrem/yr. For this juvenile failure to occur, water would have to drip directly onto a bad weld. Absent this juvenile failure assumption, penetration of a waste package wall was not be expected to occur sooner than about 4,000 years, and penetration at that time would occur only if crevice corrosion occurs.

This mode of failure was determined to lack credibility for the design used in TSPA-SR. Instead, juvenile failures were evaluated using a more elaborate model of the corrosion of the EDA II design system accounting for the likelihood of technical, administrative, and inspection failures and their distribution at the waste package surface. As discussed in Section 3.7, the resultant treatment of corrosion remains quite conservative in its treatment of the details of the corrosion mechanisms (e.g. hydrogen absorption, stress corrosion cracking, crevice propagation).

In addition, sensitivity analyses were conducted to assess introduction of an artificial juvenile failure (TRW00) at 100 years for the EDA II design. This assessment is not based on any known mechanism, and *is not considered to be a credible occurrence*. It was evaluated solely for the purpose of evaluating extreme behavior in the system and investigating the role of the waste package in system performance. In addition, the release mechanisms associated with this juvenile failure were, as discussed above, treated in a very conservative manner leading to rapid releases from the waste package. Hence, this analysis represents a comparable approach to the manner in which waste package failure was treated in the TSPA-VA. Results of this juvenile failure are shown in Figure 4-4. Even in these extreme conditions of unrealistic failure behavior at very early times, the resulting doses are not large.

4.3.2 Local Crevice Corrosion of Alloy 22

Early penetration of the corrosion-resistant Alloy 22 waste package was assumed in the TSPA-SR to occur as a result of crevice corrosion, which produces a local pit-type penetration. The Alloy 22 is assumed to be potentially vulnerable to crevice corrosion as a result of water dripping directly on it from a point in a failed drip shield. The electrochemical conditions for crevice corrosion are not expected to occur in the repository (TRW00a). This is a significant modification from the TSPA-VA design and analysis, in which crevice corrosion initiated as a result of its being under a carbon steel outer wall. As a result of this design modification, crevice corrosion of this type no longer plays a significant role in early waste package failures. Consequently, in the TSPA-SR the waste packages fail either as a result of manufacturing defects or by general corrosion. The net effect of this change in mechanism is a significantly longer expected lifetime for the containers, with juvenile failure becoming far less important than in the TSPA-VA.

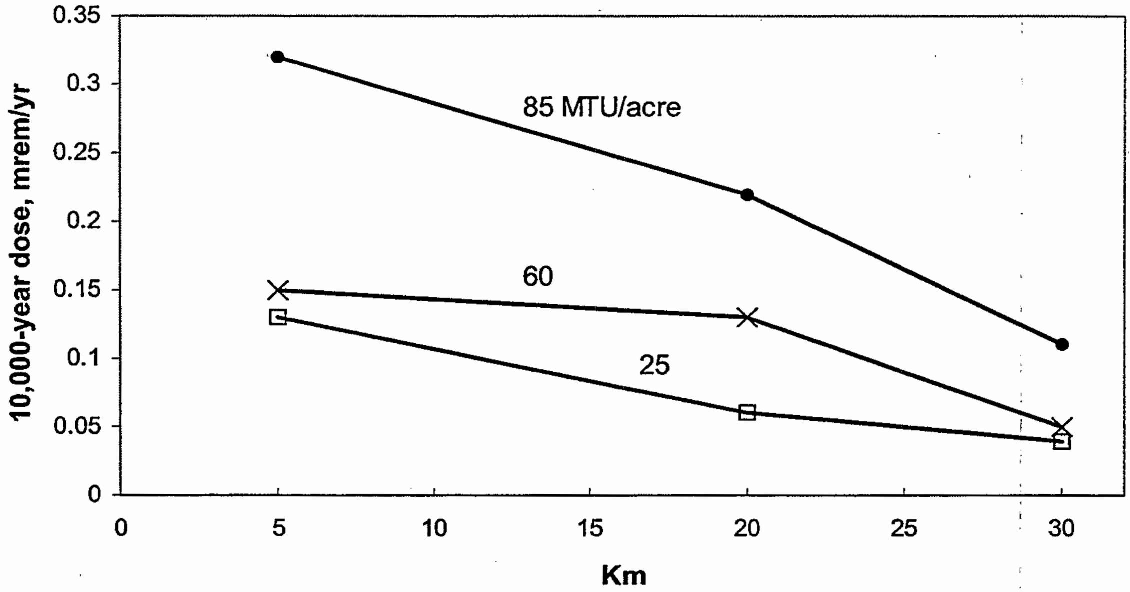


Figure 4-4. 10,000-Year Dose-Rates for Alternative Areal Mass Loadings (compiled from DOE 99)

4.3.3 Water Flow Into the Package Interior

The amount of water that enters the interior of a penetrated package and can contact the exposed waste form depends on the precipitation rate onto the top of the mountain, the fraction of the precipitation that infiltrates into the mountain, the fraction of the infiltration flow that arrives at the repository horizon as percolation flux, the fraction of the percolation flux that seeps into the drifts, the extent to which the surface of a waste package contacted by seepage flow is wetted, and the fraction of the waste package surface area that is open, as a result of corrosion, to permit seepage water to enter the interior.

Key elements of the TSPA modeling of these performance factors included the following:

- Precipitation and infiltration as a function of location in the repository footprint were characterized, for current climate conditions, using available site characterization data.

- After 600 years, the climate is assumed to change to what was termed long-term average conditions, under which the precipitation and infiltration rates are approximately five times greater than for current climate conditions. This is a modification from the TSPA-VA, in which the change was assumed to occur 5,000 years in the future. The estimate of a 600-year initiation of this wetter climate state is argued in the TSPA-SR to be representative of past climatological cycles. However, EPRI (EPR00) has suggested that this assumption does not adequately account for greenhouse effects on climate over the next few hundred years. They argue that greenhouse effects may well lead to a drier climate over a significant length of time.

- The total percolation flow at the repository horizon is assumed to be the same as the infiltration flow, i.e., there was no holdup or lateral diversion during flow through the unsaturated zone above the repository horizon. Current data do not appear adequate to justify alternatives to this assumption.

- The portion of the percolation flow that was in fractures is assumed to be available to seep into drifts.

- The surfaces of waste packages contacted by seepage flow into the drifts are assumed to be totally wetted. This assumption may well be overly conservative at low flow rates.

- Seepage water that contacts and wets a waste package was assumed to enter the package interior in proportion to the fraction of the waste package surface area that is open as a result of corrosion.

- A seepage flow model was developed in which, under current climate conditions, about five percent of the waste package inventory would be contacted by seeps into the drifts, and the seepage flow contacting each package would be on the order of 10-20 liters per year. Under long-term average climate conditions, about 25 percent of the waste packages would be contacted, and the seepage flow onto each waste package would be on the order of 100-200 liters per year. It was stated in the TSPA-VA that there "...is a great deal of uncertainty about seepage, particularly in the fraction of waste packages contacted by seepage." In addition, as discussed previously, there is recent evidence that the threshold for seepage may be much higher (200 mm/yr) than the threshold used in the TSPA-SR. Indeed, while the value of 200 mm/yr is treated as an extreme minimum value in the TSPA-SR analysis, this value was obtained in field data for the middle nonlithophysal unit of the Topopah Spring Tuff (DOE01, p. 4-92). Applying a higher threshold value would significantly increase the amount of time before the packages are wetted.

Within this modeling framework, the assumptions concerning infiltration, percolation, and seepage rates constitute conservative conditions based on currently available information. These assumptions are likely to more strongly influence the timing of the release than the potential peak. However, by delaying the release sufficiently, doses in the first 100,000 years may be dramatically decreased using alternative assumptions.

The assumption that the entire surface of a waste package that is dripped on by seepage water is wetted and therefore susceptible to aqueous corrosion is highly conservative. It is reasonable to expect that only water that drips onto a narrow band of the top of the package (e.g., at most a 20-degree arc of the 180-degree arc of the top half of the package) has real potential to initiate aqueous corrosion. To totally wet the package surface, such drips (which could occur, according to the seepage model, at a maximum rate of 10-20 liters per year under current climate conditions), would have to spread uniformly over the package surface, which has a total area of about 40 square meters. This situation would produce a water film only about 0.2 millimeters thick, which is an unrealistic condition to produce and sustain the Alloy 22 corrosion that is presumed to be the mechanism for waste package failure.

4.3.4 Exposed Waste Form Area

For commercial spent nuclear fuel (CSNF) waste packages, which are the dominant (by two orders of magnitude) source of radionuclide releases in the TSPA-VA analyses, the exposed waste form area that can be a source of released radionuclides is related directly to the status and performance of the CSNF cladding as a barrier. The TSPA-SR analyses assumed that eight percent of the cladding will be failed at the time of emplacement owing to creep failure and stress corrosion cracking. The TSPA-SR noted that "this mean percentage is very conservative and likely above the amount of creep and SCC that the NRC will tolerate of operators of dry storage facilities." The stainless-steel-clad rods were assumed to be distributed among the waste packages, and the entire CSNF area in any failed rod was assumed to be exposed for contact with water. Zircaloy cladding degradation by general corrosion and other means such as crushing by rockfall was assumed to be a long-term phenomenon of no significance to 10,000-year dose estimates.

The assumptions concerning CSNF exposed area are highly conservative. Specifically:

- Stainless-steel-clad fuel rods will not be distributed throughout the waste packages except as a result of deliberate effort. Less than one percent of the CSNF assemblies have fuel rods with stainless-steel cladding, and they probably would actually be disposed together in less than one percent of the total waste package inventory, in order to reduce personnel exposures and operating costs.

- The estimate that eight percent of the Zircaloy-clad fuel rods are failed at the time of emplacement is very conservative in comparison with available data. The observed historical incidence of failure is less than 0.05 percent, is perhaps as low as 0.01 percent, and is confined to fuel manufactured in the early days of nuclear power or subjected to external failure factors such as debris in the reactor coolant. Fuel yet to be discharged from operating reactors (about 50 percent of the ultimate repository inventory) can be expected to have no failures, so the incidence of at-emplacement rod failure in the final repository inventory will be significantly less than the historical incidence to date and significantly less than the incidence assumed for the TSPA analyses.

- In over 90 percent of the cases, "failure" of Zircaloy cladding has been found, in post-service examinations, to consist of pinhole penetrations or hairline cracks. Therefore, only a very small fraction of the fuel contained in a failed rod will be exposed as a source of released radionuclides if contacted by water. In contrast, the TSPA evaluations assumed that the entire spent fuel area in a fuel rod would be exposed for contact with water and release of radionuclides. This assumption overstates the exposed area, based on available data, by about three orders of magnitude.

- Many potential modes of Zircaloy cladding degradation, such as hydride formation and creep failure, have been identified and characterized because cladding integrity is so important in its reactor service conditions. EPA has performed and documented a comprehensive review and analysis of available information and has concluded that degradation of cladding by any of the failure mechanisms is not expected to occur under repository conditions after emplacement for disposal. The exposed waste form area will therefore be that which exists at emplacement for disposal until very long-term failures, such as package crushing by a rockfall, occur (SCA99).

Collectively, the TSPA-SR assumptions concerning exposed waste form area overstate the area available for nuclide release by about four orders of magnitude (i.e., three orders of magnitude on the exposed area per failed rod, and a factor of ten on the number of failed rods). They also overstate the potential for long-term degradation of the cladding. If realistic assumptions concerning performance of the EDA II repository are used, water would not contact the cladding for more than 100,000 years, and cladding performance would be irrelevant to dose potential before that time. Cladding performance will, however, be important to estimation of long-term peak doses. In comparison with the preliminary estimate of peak dose of 85 mrem/yr at 650,000 years for the EDA II repository (Table 4-1), a realistic estimate of cladding performance and exposed waste form area would decrease the peak dose estimate by several orders of magnitude.

It is important to note that assumptions concerning cladding performance as a barrier and the amount of waste form area exposed for radionuclide release are essentially independent of assumptions concerning performance of engineered features of the EDA II design. The link between the EDA II design features and cladding performance is the design temperature limit for the cladding. This limit is the same, 350°C, for both the VA and EDA II designs, and the expected actual maximum cladding temperature in both designs is about 250°C. The 8% failure rate used in the TSPA-SR was acknowledged to be very conservative. It represents a mean value for failure rates at low (177-227 C) temperature. However, DOE also reports the mode of this distribution as about 2 percent. Hence, the mean appears to be skewed to a high value by a few outlier high values (the maximum value is 19.4 percent). With "blending" of subassembly allocations to the waste packages in order to reduce thermal gradients, confidence in assumptions concerning cladding performance that are less conservative than those used for the TSPA evaluations would be increased.

In summary, the TSPA evaluations are highly conservative regarding cladding performance in comparison with reasonable interpretations of the available information base. Assumptions of exposed waste form area exposed for nuclide release for each failed fuel rod exceed actual exposed areas by about three orders of magnitude; assumptions concerning the number of Zircaloy-clad failed rods exceed the actual number by about a factor of 10. A realistic approach to these assumptions based on principles of Reasonable Expectation is described in Section 5. Nonetheless, despite these highly conservative assumptions, releases from the waste packages do not occur within 10,000 years according to the TSPA-SR. Modification of these assumptions may, however, improve long-term dose estimates for times greater than 10,000 years.

4.3.5 In-Package Dilution and Transport Delays

If water enters a penetrated waste package at the seepage rate or some fraction thereof, significant delay could occur before the water contacts exposed CSNF and initiates radionuclide release. For example, if the package interior fills slowly from the bottom up (as a result of trickle-down from a small hole in the top and needs first to corrode through basket materials), and if the exposed CSNF area(s) are in a subassembly near the top, thousands of years could pass before contact between the water and the exposed waste form occurs.

Subsequent to water/waste contact, released radionuclides that are mobile must be transported to the point of exit from the package interior by advective and/or diffusional processes. By the time release and transport occur, temperature gradients will be too low to drive significant advective transport processes, and temperature levels will be too low for inside-to outside wall corrosion to occur and to create an exit path at the bottom of the package. Consequently, radionuclide transport rates will be low, the package interior will have to fill with water in order to enable radionuclides to exit through the same penetration that provides water ingress, and the volume of water to fill the package interior will be available to dilute the radionuclide concentrations.

The void volume of the interior of a 21-assembly PWR waste package is about 3,000 liters. If water enters and exits the packages at rates in the range 6 to 400 liters per year, which corresponds to the seepage rate range for the TSPA-SR long-term-average climate conditions, at steady state and with complete in-package mixing, the in-package dilution factor would be in the range $3{,}000/400 \sim 7$ to $3{,}000/6 = 500$. Additional dilution would then occur during transit of the near-field, the unsaturated zone, and the SZ by the contaminated water that exits the package. Such dilution mechanisms may be particularly important for radionuclides not limited by their elemental solubilities, such as I-129.

These in-package delay and dilution possibilities were considered and analyzed in the studies described in the TSPA-VA Technical Basis Document (DOE98a). They were not, however, included in the base-case performance assessment models for TSPA-VA and TSPA-SR because of uncertainties, and an inability to justify the assumptions. If included in the models, they could have reduced the predicted TSPA-VA 10,000-year dose by one to two orders of magnitude, depending on how probabilities for the relevant performance factors are taken into account.

To incorporate these performance factors into the TSPA models, it would have been necessary to develop probability distributions for factors such as time elapsed between water entry to the package interior and time of water contact with the exposed waste form. DOE chose to develop probability distributions many of the performance factors external to the packages, but chose to omit the in-package performance factors and associated probability distributions, from the TSPA models. It is worth noting that the in-package performance factors are potentially as important to the TSPA results as climate change and seepage rate. It is reasonable, for example, to expect, at a minimum, some degree of dilution of contaminant concentrations in water exiting a waste package as a result of mixing with nearby water in the near field and the UZ.

As for the role of exposed waste form area in performance of the EDA II repository, the in-package performance factors will not be important to evaluation of 10,000-year doses if realistic assumptions concerning performance of the EDA II drip shields and waste packages are used, such as has been done in TSPA-SR. The in-package performance factors could, however, help to show that long-term peak doses will be low in the period after 10,000 years. Specifically, penetration of the EDA II waste packages will occur so far into the future that there will be virtually no thermal driving force for radionuclide release and transport in the waste package interior. Mixing and homogenization of concentrations within the waste package would have to be driven by diffusional processes.

4.4 Radiation Doses to Alternative Receptors

To date, eleven alternative dose receptors have been identified by DOE, the NAS, NRC, EPRI, and EPA as the potential basis for evaluating compliance with the individual-protection standards for Yucca Mountain. The options include alternatively-characterized individuals and critical groups. Each has, to some degree, taken cognizance of site-specific conditions and each has, to some degree, utilized ICRP principles for designating a group or individual receptor, e.g., to base assumption of the future receptor's habits on present-day habits. Each also seeks to identify and characterize the receptor with the highest dose potential, without being extreme, in order to assure protection of other individuals.

DOE's TSPA-VA, DEIS, and TSPA- SR used the so-called "average resident" as the dose receptor. This individual was located 20 km from the repository, and had habits corresponding to those of current residents, as determined in a survey performed by DOE. The TSPA-VA states that this person consumes part of his food from local sources and consumes 1.8 liters per day of drinking water contaminated with radionuclides released from the repository, at the maximum contaminant plume concentration. The DEIS, which was stated to use the same TSPA evaluation methodology as the VA, states that the average resident receptor consumes 2.0 liters of contaminated water per day. The TSPA-SR states that the average-resident receptor in Amargosa Valley consumes slightly more than 2.0 liters of water per day (753 liters per year), and this value is used in the assessment. With this water consumption rate, the DOE's average-resident is essentially equivalent to EPA's "rural residential" RMEI dose receptor.

Results of the DOE's average-resident dose evaluations at 10,000 years, based on the assumptions and methods described above in Section 3.7, can be summarized as follows:

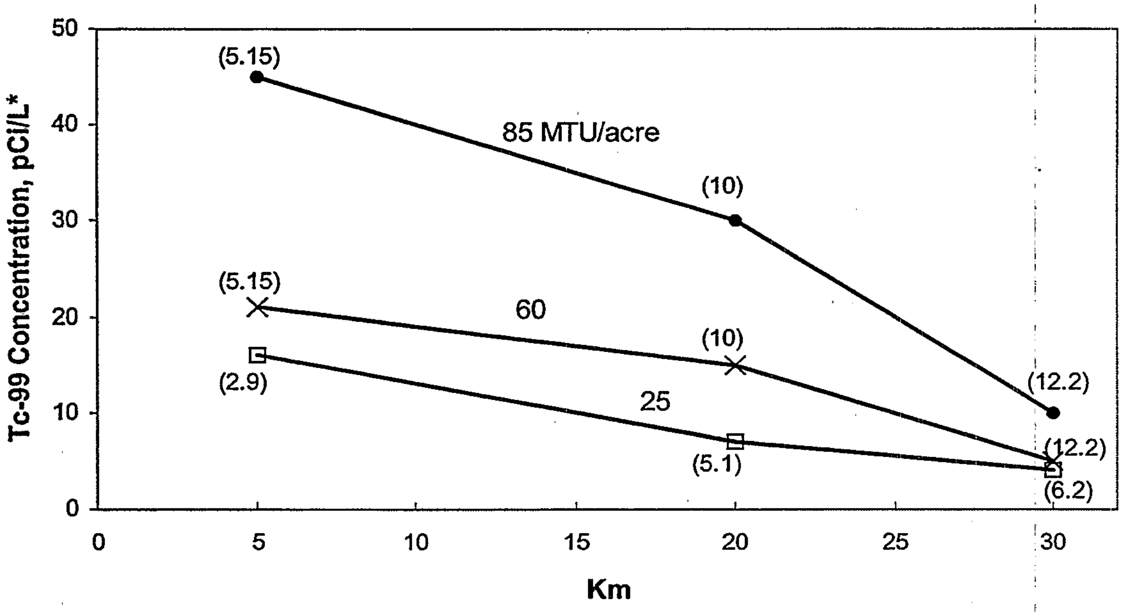
- TSPA-SR mean all-pathways dose (using probabilistic evaluations) is 0.10 mrem/yr. This value is the same as the mean value at 10,000 years for the TSPA-VA. However, this agreement is fortuitous, as entirely different scenarios are associated with the dose. For the TSPA-VA, the dose was associated with juvenile failures of waste packages that were unrealistic and gave high releases. The TSPA-SR treats these juvenile failures more realistically, and these failures do not affect pre-10,000 year doses in the TSPA-SR. By contrast, in the TSPA-SR the dose at 10,000 years is associated with igneous intrusion, with subsequent releases to ground water. This scenario appears to be highly conservative, giving unrealistically high releases as well.

- VA base-case dose using an evaluation with all parameters set at their expected values: 0.04 mrem/yr. A similar result is not reported for TSPA-SR. Instead, the range of doses at 10,000 years is about 10^{-4}-10^{0} mrem/yr (5th to 95th percentiles), with the mean about 10^{-1} mrem/yr and the median about 10^{-2} mrem/yr.

- DEIS mean all-pathways dose for the Proposed Action, which corresponds to the VA repository: 0.22 mrem/yr (this result presumably differs from the VA result of 0.10 mrem/yr because of modeling adjustments made for the DEIS evaluations in order to be able to address the DEIS options concerning waste inventories and thermal loadings).

Since the DOE's average resident corresponds to EPA's rural residential RMEI, these results are representative of the results that would be obtained using the EPA's rural-residential RMEI at 18 km as the receptor and the TSPA-SR methodology and assumptions. As previously noted, and discussed in Section 3.7, these results overstate the dose to be expected as a result of the conservative assumptions used in the evaluations.

The DEIS also evaluated doses to the average resident at alternative locations and for the alternative areal mass loadings considered. Results are shown graphically in Figure 4-4; corresponding Tc-99 concentrations in ground water, and assumed saturated-zone dilution factors at each distance, are shown in Figure 4-5. Variations of I-129 concentration with location and areal mass loading are similar to those for Tc-99, but I-129 concentration levels are about two orders of magnitude less than those of Tc-99.



* The MCL for Tc-99 is 900 pCi/l. Numbers in parentheses are the dilution factors used at each distance.

Figure 4-5. Tc-99 Concentrations for Alternative Mass Loadings (compiled from DOE99)

The reason for dose variation with areal mass loading is not evident from available documentation. For example, repository temperatures, which would affect corrosion rates, are virtually identical for the 85 and 60 MTU/acre loadings during the period from 1,000 to 10,000 years, while the repository temperatures for the 25 MTU/acre loading are about 40°C less (DOE99). Similarity of results for the 85 and 60 MTU/acre cases might therefore be expected; Figures 4-3 and 4-4 show, however, that the results for 60 and 25 MTU/acre are most similar. Also, Figure 4-4 does not show any correlation between SZ dilution factors and distance from the repository.

The variations of dose with areal mass loading may be the result of differences in repository areas and attendant differences in transport and dilution in the unsaturated zone. The 85, 60, and 25 MTU/acre repositories, for the reference inventory of 70,000 MTU of wastes, occupy 740, 1050, and 2,520 acres, respectively. The 60 MTU/acre repository occupies two emplacement blocks and the 25 MTU/acre repository is spread over several emplacement blocks. Transport and dilution in the UZ may therefore have been modeled differently for the three loading options.

While the DEIS evaluated doses for the same receptor at alternative locations and for alternative repositories, the VA characterized doses for alternative receptors. The VA reported dose evaluation results for only the average resident as receptor, but it also characterized doses for a subsistence farmer receptor and a so-called residential farmer receptor. All food and water ingested by the subsistence farmer was assumed to be contaminated; only part of the food consumed by the residential farmer was assumed to be contaminated. DOE's surveys found no current residents who correspond to either of these receptors. The characterizations determined, however, that the Np-237 biosphere dose conversion factor (BDCF) for the residential farmer would be three times greater than that for the average resident, and the BDCF for the subsistence farmer would be about six times greater. The I-129 BDCF for the subsistence farmer was stated to be about 10 times greater than that for the average resident. The VA also stated that the most important factor for doses due to I-129 and Tc-99, which are the only radionuclides of significance released in the 10,000-year time frame, is leafy vegetable consumption, and that direct consumption of contaminated ground water contributes about 50 percent of the dose.

The NRC defines a critical group as the dose receptor in the proposed 10 CFR Part 63 regulations for Yucca Mountain. The critical group is described as residing within a farming community located approximately 20 km south of Yucca Mountain. Members of the group would have characteristics that are consistent with current conditions and that result in the highest expected annual doses. The group would be a farming community of up to 100 individuals residing on 15 to 25 farms. The behaviors and characteristics of the average member of the critical group would be based on the mean value of the group's variability range.

The average member of the NRC's critical group would be predicted to incur less dose than either the DOE average resident or the EPA's rural residential RMEI, and this choice of dose receptor would therefore be less protective of the general population. Less dose would be predicted for two principal reasons: the dose conversion factors for the NRC critical group would be based on mean values of the dose factors, whereas the EPA's RMEI uses maximum values for one or more of the dose factors (e.g., drinking water rate); and the members of the farming critical group would be so spread out that only a fraction of the group would use contaminated water at the maximum concentration. The current average size of an alfalfa farm, which is the dominant farming activity, is about 255 acres; in the most compact configuration, a square, 25 farms of current average size would occupy an area more than three miles long on each side. The VA shows (p. 3-137 of Volume 3) that the contaminant plume width is only about 1 mile at 20 km distance from the repository. Many of the members of the NRC's critical group would therefore, in reality, receive no dose or significantly less than the maximum dose, so that the average would be unrealistically low. Ground water flow systems dominated by fractured rock hydrology would be expected to produce narrow contamination plumes (see the BID for descriptions of the fracture-flow dominated hydrological system at the Yucca Mountain site.)

If 25 average-size alfalfa farms are located 20 km from the repository (e.g., at Lathrop Wells), the number of farms that intercept the plume at that distance will depend on how the farms are located relative to each other. If the farms are in an east-west line, only one farm would intercept the plume. If the farms are adjacent to each other in a square, at most five farms would intercept the plume. If the farms are in a north-south line, some of the farms would extend beyond 30 km from the repository, i.e., beyond the current Amargosa Farms area (SCA00).

In summary, the dose receptors considered in DOE's TSPA-VA and TSPA-SR are similar to the EPA's RMEI as described in the rule, and may actually be somewhat more conservative. For instance, the TSPA-SR assumes slightly more than the 2 liters/day drinking water consumption specified in the rule. In addition to these earlier treatments, the critical group receptors evaluated in the TSPA-SR are subject to exposures to contaminated ash in the eruption scenario. Dose estimates in both of these TSPAs are well below the 15 mrem/yr individual protection limit, despite the use of very conservative assessment scenarios and models. Based on these considerations, the EPA's choice of an RMEI rather than a critical group for the dose receptor does not have any impact on repository development costs or progress. As described above, the proposed farming community critical group potentially makes assessment defensibility more difficult and subject to challenge, owing to the requirement for arbitrary assumptions on the size and location of farms. These may not necessarily be consistent with current and projected land use in the area, so as to ensure that all members of the critical group receive some level of exposure.

4.5 Alternative Means to Reduce Uncertainties and Doses

As noted in Section 3.4.1, principal objectives in selecting the EDA II design as the basis for the site recommendation were to improve the real performance potential of the repository and to reduce uncertainties in projections of performance. The benefits of the EDA II design are illustrated in the differences between dose projections in the TSPA-VA and the TSPA-SR, which shows that projected doses for the EDA II repository up to 10,000 years are substantially less than those for the VA repository. Indeed, the EDA II design only produces doses in the first 10,000 years as a result of potential igneous activity. In terms of performance for the nominal behavior of the system, the improvement in performance over 10,000 years is extremely dramatic. As shown in Figure 3-2, the nominal case for the EDA II analysis exhibits no releases over 10,000 years.

Overall, it can be said that the objective of the EDA II design is to defer and reduce the potential for, and uncertainties in, thermally driven degradation processes such as corrosion and advective radionuclide transport. Alternatives to the EDA II design that address this objective are illustrated by the EDA options considered, from which the EDA II option was selected for the TSPA-SR (Table 3-3). Comparison of these options shows that they reflect widely different strategies for meeting the objective. For example, the EDA I option takes a direct approach by reducing the area mass loading and repository temperatures. The EDA V design takes the opposite approach: it drives the temperatures to high levels in order to greatly defer the time at which water can enter the repository and initiate high-rate degradation processes.

Other advanced repository designs which incrementally improve the VA design might have been identified and evaluated. For example, the waste package design with the Alloy 22 on the outside could have been adopted with all other EDA II parameters except use of drip shields and backfill. This choice would have considerably increased waste package performance by eliminating the crevice corrosion process that greatly accelerated package failures in the VA design (17 packages failed by this mechanism within 10,000 years), thereby extending expected waste package lifetimes beyond 10,000 years. Another incremental design feature that could be added would be to tilt the packages along the axis at emplacement in order to have drips run off the surface, or to use weld shields rather than drip shields that cover the entire package. These are simple, inexpensive design features that could reduce the potential for juvenile failure and subsequent releases.

With respect to the impact of juvenile waste package failures, their treatment in the TSPA-VA was extremely conservative and consequently releases from such failures dominated doses within the 10,000 year period. In the TSPA-VA, an exit hole in a waste package was assumed to exist as soon as an entry hole was created. Under this assumption a juvenile failure from a manufacturing defect (weld failure) resulted in immediate releases into the waste package surroundings. In the TSPA-SR, a more realistic treatment of juvenile failures was incorporated, eliminating the extreme conservatism of the TSPA-VA treatment. These modeling changes, along with the move to an improved waste package design that eliminated the potential for accelerated failure associated with crevice corrosion, were sufficient to greatly improve the projected performance. Improving performance projections and reducing uncertainties could be done in a variety of ways, with cost impacts that vary according to the extent and nature of changes in the repository and waste package design, and according to increases in data needs for the assessment of performance.

Analysis results for the EDA options that are presented in Table 3-3 show that the options meet the objective to varying degrees and with different costs. In examining the performance factor results in Table 3-3, it is important to remember that these results were produced using the same performance models and conservative assumptions that were used to produce the TSPA-VA results. More realistic evaluations, using reasonable parameter values, models, and assumptions, would produce peak annual doses at least several orders of magnitude less than those shown in the Table. Realistic evaluations and assumptions that would lead to lower doses are discussed in Section 5, which addresses Reasonable Expectation.

To paint a realistic picture of repository performance potential, it is important to acknowledge the benefits of the design features in the models and assumptions used to make performance predictions. For example, the backfill/drip shield/waste package design features of the EDA II repository completely eliminate the real potential for juvenile waste package failures or corrosion-related radionuclide releases for 10,000 years and more. Similarly, assessments of long-term peak dose potential that use reasonably-expected parameter values and assumptions will show dose levels that are orders of magnitude less than those that have been reported to date, even without including performance factors such as in-package dilution that have been omitted from the model hierarchy to date.

In summary, the EDA II repository design, which is the basis for the TSPA-SR, is a highly conservative design with extensive redundancies that assure no radionuclide releases in the nominal scenario during 10,000 years. The design has enabled modifications to the TSPA models and assumptions that reflect the benefits of the design to repository system performance. The use of this robust design has allowed DOE to use a number of very conservative assumptions in its assessment. Modification of these assumptions to more reasonable, yet still credible, approaches would result in very significant delays in releases from the repository; there is the potential that modified assumptions would produce no significant calculated doses in the first 100,000 years.

4.6 Current Repository Design and Safety Strategy

As part of its program evolution to the TSPA-SR, DOE has recently revised its Repository Safety Strategy previously described in 1998 (DOE98d). The most recent description of the revised strategy and plans for its implementation is provided in TRW00.

The TRW00 Rev 3 strategy updates the previous version of the strategy (DOE98) which was the basis for the VA. It reflects the EDA II design (Section 3 of this document), which is the current stage of evolution of the repository design. The revised strategy also reflects recent additions to the program database; response to the regulatory framework; and internal and external comments on the VA design and TSPA-VA methodology, and the eventual implementation as TSPA-SR. Under this strategy, the postclosure safety case is based on developments and evaluations in five principal areas: performance assessment; safety margin and defense-in-depth; consideration of potentially disruptive processes and events; insights from natural analogs; and long-term performance confirmation.

The design evolution (from the VA to EDA II) and the safety strategy evolution are intended to be responsive to the concerns about uncertainties and technical issues associated with the TSPA methodology and assumptions as it evolved from TSPA-VA to TSPA-SR. The approach will reduce potential difficulties during licensing reviews by reducing or eliminating the TSPA uncertainties and issues that would create difficulties in licensing reviews.

The EDA II design and the Rev 4 Safety Strategy are the latest step in evolution of the repository concept. Over time, as shown in Table 4-3, the relative contributions of the engineered and natural system features of the repository to overall performance have inverted: site characterization has shown that the natural features will not contribute nearly as well to performance as was expected in the SCP, and the performance of the engineered barriers has been increased dramatically to compensate for the lesser natural barrier performance expectations, and to respond to licensing requirements for defense-in-depth and minimization of uncertainties and technical issues.

Table 4-2. Change Over Time of the Roles of Natural and Engineered Barriers in Repository System Performance

Project Era	Infiltration Rate	GWTT*	WP** Lifetime	EBS Features
SCP (1988)	1 mm/yr max	9K - 80K yrs	300 - 1,000 yrs	Thin-walled can, vertical in floor
Early TSPAs (1991-1995)	1 mm/yr max	9K - 80K yrs	Various designs, 300 ~ 10,000 yrs	Horizontal, robust WP considered
Viability Assessment (1998)	8-40 mm/yr now; 200 in superpluvial	As short as 50 yrs for fast paths in the UZ	Less than 20 packages fail within 10,000 years; 20,000 years for general corrosion	Horizontal WP used steel over Alloy 22
TSPA-SR (2001)	0.4-12 mm/yr now 4.7-20 in monsoon climate	Mean delay in UZ is 1,000 years and mean delay in SZ is 1,300 years	expect no radio-nuclide release for 10,000 + years	Alloy 22 on outside of WP; add drip shields

* GWTT = Ground Water Travel Time to the Accessible Environment
** WP = Waste Package

Another facet of the Safety Strategy has been an extensive evaluation of parameter uncertainty and sensitivity. The TSPA-SR (TRW00a) reported three kinds of evaluations of parameter uncertainty and sensitivity: Uncertainty Importance Analysis, Sensitivity Analysis, and Robustness Analysis. *Uncertainty Importance Analysis* refers to the use of regression analyses to determine the most important parameter contributors to the spread of output results, and classification-tree analyses to determine the parameters leading to extreme outcomes in the distributions. *Sensitivity Analysis* refers to single-parameter sensitivity analyses, in which one parameter is varied while the others are held at particular values. *Robustness Analysis* (also referred to as Degraded Barrier Analysis in the TSPA-SR) refers to a focused approach to examining parameters associated with extreme degradation behavior of individual barriers, keeping intact the remaining analysis of the system.

Uncertainty importance analyses were performed beginning with stepwise linear rank regression analysis. The results of these analyses were evaluated using classification and regression tree analysis to determine decision rules that determine whether a particular realization would produce doses at the upper or lower end of the output distribution. These approaches were used to evaluate the spread in doses at a particular time and the spread of times needed to produce a particular dose. Particular attention was also focused on the extreme high end of the output distribution, to determine which parameters lead to the extremes of the output.

The uncertainty importance analyses showed that the waste package and saturated zone processes are the most important factors in the nominal scenario, whereas the probability of the occurrence of igneous disruption of the repository is the most important factor for igneous scenarios. As discussed in the TSPA-SR, the assessment that these are the "most important" in this uncertainty importance analysis reflects two factors: the change in variance of dose rate with variance of the parameter, and the change of the dose rate itself with changes in the parameter. If either of these two derivatives is small, the techniques used in the TSPA-SR will tend to show the parameter to be unimportant.

Sensitivity analyses, as used in the TSPA-SR, refer to a single parameter variation method. This is considered to be a complementary technique to the uncertainty importance analysis. In this approach, a single parameter was ranged between its 5th and 95th percentiles, and other parameters were fixed at particular values.

The robustness analyses were conducted by setting a suite of parameters associated with a particular barrier at their 5th or 95th percentile, whichever tends to maximize the dose rate over the time period of interest. For the sake of completeness, the results are also shown compared to results from the same suite of parameters set at the opposite end of the behavior (i.e., values which tend to minimize dose consequences). The intent of these robustness analyses is to present the behavior of the system as a whole if any part of the system degrades quickly, and functions according to its extreme behavior. Robustness analyses were conducted on nine facets of system behavior (TRW00a):

- UZ. This barrier represents the function of the UZ above the potential repository in limiting the amount of water that reaches the potential repository. This barrier includes the climatic conditions at Yucca Mountain, the processes at and near the surface that lead to infiltration, and flow through the UZ above the potential repository. Parameters treated in the robustness analysis were the seepage-uncertainty factor and the flow-focusing factor. Degraded conditions for these parameters resulted in a small increase in dose rate over the base case.

- Seepage into emplacement drifts. This barrier represents the function of the drifts themselves as a capillary barrier that limits the amount of water that enters the drifts. Both infiltration and seepage parameters were set to their degraded behavior for this analysis. Degraded conditions for these parameters resulted only in about a factor of 5 increase in dose rate over the base case.

- Drip shield. The first of the engineered barriers, the drip shield limits the amount of water that reaches the waste package. In the robustness analysis, the general corrosion rate parameters were set to their extreme values. While the drip-shield lifetime is significantly degraded in this analysis, there is almost no change in the dose rate. This results reflects the fact that the waste package degradation model is independent of the drip shield function. This appears to be an example where the high degree of conservatism in one model masks the importance of a different function, as discussed in TRW00a.

- Waste package. The primary engineered barrier, the waste package limits the amount of water that reaches the waste form and limits radionuclide transport out of the EBS. Degradation parameters considered in the robustness analysis were: residual hoop-stress state and stress intensity factor at the closure-lid welds; number of manufacturing defects at the closure-lid welds per waste package; Alloy-22 general corrosion rate; microbially-induced corrosion enhancement factor for general corrosion; and enhancement factor for Alloy-22 general corrosion from aging and phase stability. The enhanced case (optimistic parameters) led to no releases from the waste package for the first 100,000 years. The degraded parameters show a somewhat earlier failure profile, with first failure occurring at 7,000 years compared to 12,000 years for the base case. For the degraded case there is 50 percent probability that 1 percent of waste packages fail at about 10,000 years and 10 percent of waste packages fail at about 12,000 years. For the base case it is about 25,000 years for the 1 percent failure and about 50,000 years for the 10 percent failure. Accordingly, the predicted mean dose starts earlier (about 8,200 years versus about 15,000 for the base case), and the predicted mean dose rates are much higher.

- CSNF cladding. The Zircaloy cladding is an engineered barrier that is part of the waste form. It limits the amount of water that reaches the CSNF portion of the waste and limits radionuclide transport out of the CSNF waste form. (CSNF is planned to be approximately 90 percent of the mass of waste in the potential repository.) Four of the five parameters in the cladding degradation model were evaluated in the robustness analysis: the number of rods initially perforated in a CSNF waste package, the uncertainty in localized corrosion rate, the uncertainty of the CSNF degradation rate, and the uncertainty in the unzipping velocity of the cladding. It was concluded that these parameters are unimportant for performance in the first 100,000 years, but that they contribute to the spread of doses during the period 100,000-1,000,000 years. The effect of these parameters on dose rate in the robustness analysis is not reported by TRW00a.

- Concentration limits. This barrier represents the function of environmental conditions and radionuclide solubility limits in limiting radionuclide transport out of the EBS. The primary dose contributor in the first 30,000 years is technetium-99. The solubility of Tc-99 is assumed to be large (1 M), and is not treated as uncertain. The primary radioelements for the period after 30,000 years are neptunium, americium, and uranium. The solubilities of each of these is controlled by pH in the TSPA-SR model. The pH, in turn, is assumed to not vary widely in the invert. This limits the variability of the dose rate as a function of any other factors in the near-field model. In particular, TRW00a notes that most of the releases are by a diffusive mechanism, hence controlled by diffusion-related parameters. This too appears to be an area in which a strong structural conservatism of the model (in this case the assumed diffusional releases) tend to mask the importance of other effects.

- EBS transport. This barrier represents the function of environmental conditions and diffusion in the drift invert in limiting radionuclide transport out of the EBS. In this case of the robustness analysis, the combined effects of degraded concentration limits and high diffusion cases. The results are reported as a decrease in the time to early-arrival doses (defined as time to 10^{-3} mrem/yr) of several thousand years, and an increase in the peak dose rate of about a factor of five.

- UZ transport. This barrier represents the function of the UZ below the potential repository in delaying radionuclide transport to the biosphere. An extensive set of robustness analyses were presented for this function. The degraded cases showed between a factor of 5-10 higher dose rates than the base case, whereas the enhanced cases showed significantly improved behavior (many orders of magnitude) over the base case. That is, since the base case is little different than the degraded case but very different than the enhanced case, this means that the base case is strongly biased toward the conservative end of the spectrum of behaviors.

- SZ. This barrier represents the function of the SZ in delaying radionuclide transport to the biosphere. The robustness analysis was used to investigate parameters associated with travel time in the saturated zone: sorption, and flow rate. The difference between degraded and enhanced performance in these analyses is between one to two orders of magnitude, with the base case very close to the upper end of this variability. Again, this indicates a strong bias toward conservatism in the base case.

The TSPA-SR explicitly acknowledges that the results of these analyses are dependent upon the scenarios and conceptual models implemented in the TSPA-SR. They note that the conservatism of parameter values and assumptions may tend to mask the importance of some of these to the results, or may mask the importance of others. Two of these situations were noted above in the discussion of robustness analysis: the conservatism of the drip shield treatment masks the importance of the waste package behavior, and the assumption that diffusion dominates releases together with an assumption of high solubilities tends to mask the importance of other phenomena in the waste package. These assumptions therefore compound the conservatism of the analysis, since they are, by themselves, conservative, and they also minimize the functional importance of other barriers.

The strong reliance on evaluations of parameter sensitivity and uncertainty analyses skews the evaluation of the TSPA-SR results. Instead, the model is in some cases so structurally biased toward conservatism that appropriate conclusions cannot be drawn. For instance, one conclusion of the TSPA-SR is that the primary factor influencing the consequences of the igneous scenarios is its probability of occurrence. All other parameters investigated in the sensitivity analysis were found to have relatively minor influence on the dose from igneous disruption. However, as discussed previously, such a conclusion ignores the heavy conservative bias of the consequence modeling assumptions. Given the extremely conservative basic assumptions of the consequence model, one would not expect parameter variations to significantly affect the results. By contrast, changes in the basic assumptions about interaction of magma and waste containers could decrease releases and their associated doses by orders of magnitude, or eliminate them altogether.

Similarly, the use of a model for release from the waste package in the nominal scenario that assumes diffusion in the absence of significant amounts of water near the package, results in a significant conservative bias. This assumption and associated model masks the importance and utility of the presence of the drip shield. The lack of significance of the drip shield in the TSPA-SR nominal case is therefore seen to be an artifact of the conservative bias of the waste package release model, rather than a fundamental property of the repository.

The reliance on evaluations of parameter uncertainty illustrates (potentially deceptively) small uncertainties in relatively high consequences associated with the repository. Uncertainties in parameters, as shown by the robustness analyses, lead to at most about an order of magnitude increase in dose rate under unfavorable conditions. Application of favorable sets of parameters were shown to potentially decrease the dose rate by several orders of magnitude in some cases, and to push the doses out to much longer times, in some cases past 100,000 years. By contrast, uncertainties in assumptions (conceptual model uncertainty) have the potential to lead to dramatic improvements in consequence analyses. Alternative conceptual models for the igneous scenarios have the potential to lead to minimal or zero releases from these effects, thus eliminating the consequences associated with igneous activity. Alternative conceptual models for the waste package in the nominal scenario would likely show early releases at much later times, perhaps with minimal release in the first 100,000 years. In addition, the use of less extreme assumptions may lead to a better understanding of the effects of design features such as the drip shields. Consideration of these less conservative, yet defensible and physically realistic, models is consistent with the principles of Reasonable Expectation (see Chapter 5), as well as with the concept and intent of Importance Analysis (KOZ97).

5.0 EPA'S "REASONABLE EXPECTATION" APPROACH TO REPOSITORY PERFORMANCE PROJECTIONS

This chapter discusses reasonable expectation and reasonable assurance as concepts to be used in implementing the standards. We believe the reasonable expectation approach is more appropriate for repository compliance determinations and provides a more realistic link between design and anticipated performance in the iterative process of developing a repository design for licensing.

5.1 Overview of Reasonable Expectation

The impact of the EPA standards on repository design and data collection is complicated by the fact that NRC will adopt and implement the standards, as mandated by the NWPA. The NRC is therefore the agency that determines what is needed to comply with the EPA standards. The method of implementation of the standards then becomes a deciding factor in evaluation of compliance. This chapter discusses the issue of compliance methodology, i.e., reasonable expectation versus reasonable assurance.

The EPA standards call for use of "reasonable expectation", rather than "reasonable assurance," as a basis for assuring compliance with the EPA standards. Reasonable expectation and reasonable assurance are both compliance assessment approaches and can be distinguished as discussed below. In brief, the intent of reasonable expectation is to recognize the inherent uncertainties involved in repository safety performance evaluations, and to encourage realistic treatment of the uncertainties in performance assessments and evaluations of compliance with the disposal standards. Reasonable expectation takes what might be termed a realistic or best-value approach to dealing with uncertainty in performance projections when compliance issues are complicated by uncertainties imposed by extrapolations of data and projections of performance over long time periods. Reasonable assurance is a concept that has been used in the licensing of facilities which involve only short term extrapolations of performance.

In developing a repository design, there is an iterative process between design and performance assessment that evolves over time to a final design and compliance calculations that are presented for licensing. A process that recognizes and deals realistically with inherent uncertainties would offer an efficient approach to optimizing design and performance.

The 40 CFR Part 197 standards require that DOE demonstrate compliance with the individual-protection, human-intrusion, and ground water protection standards under principles of "reasonable expectation." The standard states, at §197.14, that reasonable expectation requires less than absolute proof, because absolute proof is impossible to attain for disposal due to the inherent uncertainty in projections of long-term performance. The rule also states that Reasonable Expectation (RE) focuses performance assessments and analyses upon the full range of defensible and reasonable parameter distributions rather than only upon extreme physical situations and parameter values.

The Preamble to the proposed 40 CFR Part 197 (EPA99) described RE and its use as follows:

> *In carrying out performance assessments under a "reasonable expectation" approach, all parameters that significantly affect performance would be identified and included in the assessments. The distribution of values for these parameters would be made to the limits of confidence possible for the expected conditions in the natural and engineered barriers and the inherent uncertainties involved in estimating those values. Selecting parameter values for quantitative performance assessments would focus upon the full range of defensible and reasonable parameter distributions rather than focusing only upon the tails of the distributions as is more commonly done under the "reasonable assurance" approach. The "reasonable expectation" approach also would not exclude important parameters from the assessments because they are difficult to quantify to a high degree of confidence.*

5.2 Prior Consideration and Use of Reasonable Expectation

Reasonable expectation is the basis for evaluation of compliance with the Subpart B and C standards in EPA's 40 CFR Part 191 (amended at 58 FR 66414, Dec. 20, 1993), and is implemented in 40 CFR Part 194, the criteria for certification of WIPP (61 FR 5224, February 9, 1996). Use of the concept was upheld by the U.S. Court of Appeals, First Circuit, in its decision concerning the suits brought against the EPA for the 40 CFR Part 191 standards issued in 1985. The Court stated, in its decision:

> *Given that absolute proof of compliance is impossible to predict because of the inherent uncertainties, we find that the Agency's decision to require "reasonable expectation" of compliance is a rational one. It would be irrational for the Agency to require proof which is scientifically impossible to obtain. Any such purported absolute proof would be of questionable veracity, and thus of little value to the implementing agencies. Nor can we say that this provision is arbitrary and capricious because it will afford the implementing agencies a degree of discretion, since such imprecision is unavoidable given the current state of scientific knowledge. Thus we are again faced with a decision that is within the Agency's area of expertise and on the frontiers of science, and, as such, we refuse to substitute our judgment for that of the Agency.* (824 F.2d 1258 (1st Cir. 1987, at page 1293)).

The use of reasonable expectation is the same in 40 CFR Part 191 and 197. Part 191 states, at §191.15, Individual-Protection Requirements:

> *Disposal systems for waste and any associated radioactive material shall be designed to provide a reasonable expectation that, for 10,000 years after disposal, undisturbed performance of the disposal system shall not cause the annual committed effective dose, through all potential pathways from the disposal system to any member of the public in the accessible environment to exceed 15 millirems (150 microsieverts).*

The individual-protection standard for Yucca Mountain is stated, in §197.20, as:

> *The DOE must demonstrate, using performance assessment, that there is a reasonable expectation that, for 10,000 years following disposal, the reasonably maximally exposed individual receives no more than an annual committed effective dose equivalent of 150 microsieverts (15 millirem) from releases from the undisturbed Yucca Mountain disposal system. The DOE's analysis must include all potential pathways of radionuclide transport and exposure.*

5.3 Comparison of Reasonable Expectation and Reasonable Assurance

Reasonable expectation can be compared to reasonable assurance, used by the NRC in licensing of nuclear power reactors and other engineered fuel cycle facilities. In engineered facilities licensed by the NRC, parameter values usually lie within a narrow range around an expected value which is well known as a result of testing and experience, and the range itself will be based on actual testing and experience. For example, testing multiple samples of an alloy to measure the brittle fracture strength will result in a mean value with a small range of variability.

For reactors, the projected performance of engineered components of the facilities can be verified during their in-service lifetimes, which are only a few decades long. Consequently, the extrapolation of laboratory testing results over the relatively short reactor operating lifetime allows confirmation of the projections. This "real time" verification has been a part of the licensing experience for power reactors. Extrapolation of important natural processes in reactor licensing is limited to predictions of seismic hazards which in practice is done only for short periods of decades.

In contrast, repository performance projections involve the extrapolation of natural processes and events, and laboratory performance testing of engineered materials over time periods of 10,000 years and beyond. Such extrapolations have to date been applied only to WIPP in EPA's certification of that disposal facility.

All engineered elements of a reactor are subject to performance verification, integrity of welds can be confirmed, quality of construction can be verified, and training of personnel can be confirmed. The NRC can, therefore, establish a measured pedigree for every factor important to system performance and can expect and require, to a very high degree of assurance, that the facility will operate as intended and expected. Principles and methods of reasonable assurance were developed to serve these circumstances. Transferring reactor licensing experience and expectations unaltered into regulatory decision making for deep geological disposal is not an appropriate adoption of reasonable assurance used for licensing of reactors and other fuel cycle facilities. In adapting the reactor-based reasonable assurance to the geologic repository application, NRC has adopted a weighted probabilistic approach to evaluate performance projections. This approach moves significantly toward a recognition of the inherent differences between reactor licensing and deep geological disposal (e.g., the difficulty in verifying long time frame performance projections). However, a probabilistic approach does not, by itself, unequivocally guarantee that repository performance projections will appropriately incorporate the inherent uncertainties in these projections in a way that is not excessively conservative.

In contrast to reasonable assurance, reasonable expectation takes into account, for long-term, deep geologic disposal, the fact that many relevant performance parameters cannot be clearly characterized as can those for an engineered facility with a forty-year lifetime. Specifically, many natural features important to repository performance cannot be extensively characterized, and many exhibit a high degree of inherent variability. In addition, performance characteristics of engineered features of the repository must be extrapolated well beyond the time period for which measurements can be made.

For example, ground water flow in the volcanic rocks in the vicinity of Yucca Mountain will occur primarily in fractures which have highly variable physical characteristics such as width, length, and connections to other fractures. Tests can establish characteristics of fractures for locations where the testing was done, but testing at various locations will produce different results, which can vary widely. (Reflecting these variations, yield from water supply wells located in fractured rocks can vary widely over short distances.) In addition, the hydrological behavior of a fractured rock system can change over time, as tectonic processes and seismic activity readjust the stress state in the area. Fracture networks could be enlarged, and their connectivity and flow behavior could be gradually altered either favorably or unfavorably over long time periods. In aggregate, thorough test results will produce a picture of what is a reasonable interpretation of the range of results, and this would be the basis for implementation of the concept of reasonable expectation. It would not be reasonable to base performance assessment models and parameter values only on results which show limited fractures and limited flow, or on results which show extensive fracturing and high flow rates.

A specific example for Yucca Mountain is the case of so-called bomb-pulse Cl-36 detected at the repository horizon in the Exploratory Studies Facility (ESF) (FAB98). These data indicate that there are pathways in the rock formations above the proposed repository horizon that can rapidly transmit infiltration water to the repository horizon in about 50 years; the pathways may extend to greater depths. However, the data showed that the bomb-pulse Cl-36 was present in only a small fraction of samples taken at the repository horizon, and these results could be correlated with well-known fractures (FAB98).

These results demonstrate that it would be reasonable to expect that some relatively small fraction of the entire UZ flow will occur via fast paths, and that modeling of UZ flow should take this into account. It would not be reasonable, however, to base the evaluation of UZ performance on fast paths alone. The reasonable expectation is that most of the UZ flow and radionuclide transport will occur in accord with the bulk characteristics of the UZ geohydrologic regime.

In comparison with the reasonable assurance concept, reasonable expectation accommodates the necessity for performance assessment results for a geologic repository to recognize the inherent uncertainties and limitations of characterizing the natural system. Performance models can be defined with as much mathematical sophistication as they are for reactors, and the analyses can be as analytically complex as they are for reactors, but some of the models and parameters used in repository performance analyses will inherently be less well defined than those used for reactors. This can lead to particularly difficult problems if parameters are expected to be measured to too high a degree of confidence, accuracy, or precision; in such a case, excessive conservatism may be applied in an attempt to offset the inability to meet these unrealistic data objectives.

The analyses should be based on reasonable models and reasonable parameter values, not biased toward extremes by unrealistically conservative assumptions and parameter value selections. This approach recognizes that uncertainty encompasses the high-end aspects of performance potential, as well as the worst-case potential.

5.4 Use of Reasonable Expectation for Yucca Mountain

Given the long time frame of the regulatory period for geologic disposal, the possibility that changes in the repository system will occur over time, and the fact that, unlike reactors, prediction with certainty of such changes and ability to remedy them is not possible, assumptions concerning the agents and means of change are necessary. Similarly, assumptions are needed concerning performance factors that are difficult or impossible to characterize reliably, such as the extent to which dripping water will wet the surface of a waste package. Reasonable expectation requires that assumptions are reasonable, rather than purely biased toward conservatism, and that performance factors that can be identified and potentially have a significant impact on performance be reasonably valued and not omitted from the models and evaluations simply because they are difficult to characterize. Consistent selection of conservative parameter values, and omission of beneficial aspects of performance, because accurate characterization is difficult, would result in unduly conservative performance assessments that represent situations of very low probability. Decision-making using such analyses would be unavoidably biased.

It is reasonable to expect, for example, that climate conditions in the future can be estimated and bounded on the basis of evidence of past and present climate conditions. It would be unreasonable, however, to assume that future climate conditions will be extreme in comparison with the past. Also, in implementing the NAS finding that future performance of geologic features can be bounded for periods up to one million years (NAS95), it would be reasonable to base the assumptions on reasonable, not extreme, interpretations of past processes and events. Similarly, it is not reasonable to assume that long-term changes will always be in the direction of worsening performance, and to exclude positive aspects of such changes.

One of the most important aspects of reasonable expectation is to make reasonable assumptions concerning performance factors that are difficult to quantify with confidence. There are numerous performance parameters that can contribute significantly to system performance, but are difficult to quantify accurately, such as the area of a waste package wetted by dripping water and the area of spent fuel exposed in a breached fuel rod. To establish a realistic characterization of the performance capability of the engineered barrier system, it is necessary to make reasonable estimates for these factors and to include them in the performance models. As discussed in Section 4.3, DOE used highly conservative assumptions for such factors in the TSPA-VA evaluations or omitted them from the models because they were difficult to quantify. Our studies have convinced us that the TSPA-VA results were consequently highly conservative and understated the performance potential of the disposal system by several orders of magnitude.

The effects of some of the TSPA-VA conservative assumptions on results of the TSPA-VA evaluations can be estimated as follows:

- Assumption that the waste package is as wide as the drift: conservative by a factor of three, since the package diameter is about one-third that of the drift.

- Assumption that the Alloy 22 is penetrated rapidly as a result of crevice corrosion: conservative by a factor of 25, since the crevice corrosion rate was assumed to be 25 times higher than the general corrosion rate. This assumption was subsequently modified to reflect the updated EDA II design, and this mode of degradation was eliminated from TSPA-SR.

- Assumption that stainless-steel clad fuel rods are distributed among all packages and fail immediately when the package is penetrated by water: conservative by about a factor of about 10, since these rods can be packaged together in about one percent of the total number of packages, and radionuclide releases were assumed to occur from Zircaloy-clad fuel rods as well as the stainless-steel clad rods.

- Assumption that 0.1 percent of the Zircaloy-clad rods are failed at the time of emplacement: conservative by a factor of 5-10, since an extensive database shows that 0.05-0.01 percent are failed.

- Assumption that the entire waste form area in a failed fuel rod is exposed and leaches radionuclides when contacted by water: factor of 100 to 1,000; data show breaches of cladding are primarily small hairline cracks, and all evidence shows that no significant deterioration of cladding is expected after disposal.

Overall, many of the assumptions used in the TSPA-VA analyses can be shown, as illustrated above, to have understated the reasonably expected performance of the repository by at least three to four orders of magnitude. These arguments apply to the TSPA-VA, as a mechanism for illustrating the concept of reasonable expectation.

Consideration of reasonable expectation in the TSPA-SR evaluations for the EDA II repository design included the following:

- Use of a base case that is based on expected performance of the drip shields and the waste package. As shown in the TSPA-SR, under these conditions, no radionuclide releases would be expected for more than 10,000 years. Early waste package failures were treated as possible, but their likelihood evaluated probabilistically and shown to be unimportant in 10,000 years.

- Realistic estimates of seepage rates, the fraction of seeps that drip onto the drip shields and subsequently onto waste packages, and the fraction of waste package surfaces that is wetted. Realistic estimates can be based on emerging data which show that the seepage threshold may be as high as 200 mm/yr, i.e., 20 times higher than the estimate of current infiltration rates. These were not used in the TSPA-SR (a mean threshold of only 10 mm/yr was used), but may be included in future iterations of the TSPA.

- Realistic estimates of the rate and mechanisms of penetration of the waste package wall by corrosion. A rapidly growing database for corrosion of the wall materials replaced the assumed values used in the TSPA-VA that were based on expert elicitation results.

- Improved estimates of the rate at which water can enter the waste package interior through wall penetrations were not used in TSPA-SR, but could be adopted for future iterations. Models of penetration blockage that were recognized for the TSPA-VA and TSPA-SR evaluations but not included in the models can be adopted. Modified assumptions for these effects would likely results in releases occurring at significantly later times than found in the current model.

- Realistic estimates of the time required to achieve contact between water that enters a waste package and the exposed waste form. As a result of low seepage rates and limited entry pathways, the elapsed time to fill the package interior and achieve water/waste contact can be tens of thousands of years.

- Realistic estimates of the duration and means for radionuclides mobilized from the waste form to transport within, and exit, the interior of the waste package. As discussed in Section 6.3, release of radionuclides from the package interior would be expected to be controlled by extremely slow diffusional processes. By contrast, the diffusional model included in the TSPA-SR is highly conservative, to the extent that the majority of the releases are by diffusion. Modification of these assumptions would lead to a qualitatively different type of release rate, in which significant releases would not occur until substantial breaching of the waste container would permit advective flow to dominate. Accommodating these alternative assumptions would likely delay releases from the facility for tens of thousands of years.

- Realistic estimates of radionuclide transit times and concentrations for migration from the repository to the dose receptor location. The expanding database for the UZ and SZ regimes should enable databased estimates of UZ and SZ flow and transport.

- Realistic estimates of radionuclide concentration dilution associated with pumping by the dose receptor. As previously noted, this performance factor was omitted from the TSPA-VA and TSPA-SR evaluations. Realistic studies including those done by the NRC staff for the Issue Resolution Status Reports, indicate that the dilution factor for this performance factor could be in the range 10-50.

- Realistic estimates of the type of igneous activity expected in the Yucca Mountain region rather than extreme strombolian events could be incorporated in future TSPAs. Changing this assumption, by itself, may eliminate or greatly reduce the consequences of an entire scenario (eruption) from the dose results of the first 10,000 years, although not necessarily eliminating the occurrence of the igneous event.

- Realistic models of the contact between magma and waste packages, which account for temperature decreases, may eliminate all consequences from igneous scenarios. By accounting for these effects, the potential exists for the repository to be a zero-release facility during 10,000 years.

Implementation of these applications of reasonable expectation would be expected to predict that no radionuclide releases will occur until more than 10,000 years after disposal. In addition, long-term dose rates would occur at much later times, and be significantly lower than those published in the TSPA-SR.

In the TSPA-SR, as discussed in Chapter 4, DOE has introduced a variety of "uncertainty importance" analyses, intended to investigate the extreme ends of output distributions. These analyses include regression analysis and classification tree analysis (TRW00a). Regression analysis involves conducting stepwise linear rank regression between total dose and all input parameters, to determine the strength of the relationship between parameters and the output they produce. Classification tree analysis is a method for determining which variables or groups of variables produce a particular category of results. In particular, this approach is used to look at extremes in the output range, and to categorize which input parameters are associated with those extremes.

Since these uncertainty importance analysis techniques are focused purely on parameter uncertainty, the degree to which they are consistent with the concept of reasonable expectation depends on the conservatism of the underlying models and scenarios expressed by the parameterizations they represent. For scenario and model representations that are reasonable representations of the expected phenomena, it may well be appropriate to investigate and act upon the boundaries of the output distributions. However, if the scenario and model descriptions themselves are highly conservative, then making decisions based on the extrema of the parameter distributions compounds the conservatism, and is not consistent with reasonable expectation. As discussed in Chapter 4, several examples of models in the TSPA-SR appear to be so conservative that they fall outside of the realm of expected system behavior, and the tails of the parameter distributions appear to compound these conservatisms.

The igneous scenarios in the TSPA-SR appear to be an example of compounding conservatisms. The annual probability of occurrence is highly uncertain, and one must look to the high end of the possible values for the probability to consider the scenario at all, based on NRC guidance on probability of scenarios (NRC99). The scenario description itself is for an extreme type of volcanic event in a location in which such events are highly unlikely. The model for magmatic interaction with the waste packages also takes extremely conservative assumptions, so that waste packages are entirely destroyed, and the radionuclides are mobilized as an extreme finely ground-up, easily dispersed powder. Despite these extreme assumptions, the central tendency of the output distribution associated with parameter uncertainty provides a probability-weighted mean dose of around 10^{-2} mrem/yr (see Figure 3-3). However, the distribution that produces this value includes a few realizations of very low probability with substantial doses. Figure 6.1-2 of TRW00a illustrates that a few realizations produce doses in excess of 10 mrem/yr in the first 10,000 years. The potential exists to use uncertainty importance analysis methods to identify conditions (input parameters) that lead to these high doses, and to use that information in decision making: for example, to seek design modifications to the repository to mitigate them. However, the concept of Reasonable Expectation would recognize that it is inappropriate to use the results of extreme values of parameters applied in an extremely conservative model in an extremely conservative scenario for prudent decision making. Similar, though less extreme, examples are possible to elaborate for the nominal scenario of TSPA-SR as well.

5.5 Impact of Implementation of Reasonable Expectation for Yucca Mountain

The concept of Reasonable Expectation was developed by EPA to recognize that "absolute proof" of repository performance projections can not be obtained in the commonly understood meaning of the term, because of the long time frames and inherent uncertainties of the extrapolations involved in projecting repository performance. The approach, however, is intended to encourage realistic assumptions and assessments of repository performance, which recognize these inherent limitations. "Bounding" approaches that exclude important processes which will affect performance because these processes are not readily quantified with high precision and accuracy, or that frame performance scenarios unrealistically, have the danger of disguising important aspects of the site performance. The effect of overly conservative analyses can be to drive repository design efforts to unnecessary extremes or to set performance expectations beyond what can be reasonably demonstrated with conservative but reasonable analyses.

As discussed above, the EPA standards for Yucca Mountain were developed under the concept of reasonable expectation. In examining the conservative basis for the TSPA-SR results, a reasonable expectation approach to framing the performance scenarios and assumptions indicates that expected performance would be orders of magnitude better than the TSPA-SR results. This difference would be more than enough to compensate for the uncertainties in the assessments.

We believe the reasonable expectation approach is more appropriate for repository compliance evaluations and provides a more realistic link between design and anticipated performance in the iterative process of developing a repository design for licensing.

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6.0 COST IMPACTS OF THE STANDARDS IN THE RULE

Preceding sections of this EIA have provided perspectives on the evolution of engineered design features for a repository at Yucca Mountain; the evolution of understanding of the performance potential for natural features of the Yucca Mountain site; the relationship between engineered and natural barrier contributions to repository system performance; and the series of repository system performance assessments that have provided insights leading to the current repository design concept.

This section discusses the impact of the EPA's individual-protection standard, human-intrusion standard, and ground water protection standard on the costs of the Yucca Mountain program and the costs of the repository. Section 6.1 underscores the fact that individual-protection standards are fundamental to radiation protection, and that the costs for the Yucca Mountain program and repository design have evolved independent of the EPA IPS. Section 6.2 notes that the HIS is the same as the IPS, and that it imposes no incremental costs. Section 6.3 demonstrates that the GWS also imposes no incremental cost impacts.

In sum, the data and analysis requirements are the same for evaluating compliance with the IPS, HIS, and GWS standards, and the Yucca Mountain program, repository design, and costs have evolved without having been driven by the EPA standards.

6.1 The Individual-Protection Standard

As previously noted, the need for an individual-protection standard is fundamental to radiation protection in general and to protection of health and safety for deep geologic disposal of radioactive wastes. The issue here is not whether or not to have a standard; the issues are, what level of protection should be required, and is there a cost impact of a standard that is more stringent than an alternative? The choices under consideration are the 15 mrem/yr (CEDE) standard selected by EPA and the 25 mrem/yr standard advocated by the NRC.

The issue concerning incremental cost for the more stringent standard can be addressed by determining if there are any data collection requirements or design improvements imposed by the more stringent standard. For Yucca Mountain, the basis for assessing the need for incremental cost is provided by considering the information presented above in Sections 3 through 5 concerning the design features and projected performance for the EDA II design. As discussed in Sections 3 and 4, the TSPA-SR shows mean doses two orders of magnitude less than the 15 mrem/yr standard for the reference individual at 10,000 years and 20 km, and the reference individual corresponds to the EPA's proposed RMEI. In addition, these doses are only realized for a highly catastrophic and unlikely volcanic event.

The assessment results are based on highly conservative assumptions, to the point that some of them are highly unrealistic. Despite the conservatism, the results still showed potential to demonstrate compliance with EPA's proposed individual-protection standard. If the EPA's approach of "reasonable expectation" was used to frame the igneous scenario and assumptions, the projected dose results may have been negligible during the first 10,000 years.

The spread of the dose curves associated with parameter uncertainty shows that uncertainty in the peak dose covers at least 5 orders of magnitude during the first 10,000 years (see Figure 6.1-2, TRW00a). A very few of the realizations appear to have extreme consequences, to the extent that mean value is strongly biased by the high dose results. Indeed, for a portion of the curve this bias is so strong that the mean value exceeds the 95th percentile of the dose curves. This suggests that the mean dose curve is strongly influenced (perhaps unduly influenced) by a few realizations representing the extreme tails of the distributions. In viewing these results, it must also be kept in mind that the curves are themselves the result of the scenario and model assumptions discussed above. Modification of these assumptions to reflect more reasonable system behavior would likely decrease all of the output dose curves to negligible values in the first 10,000 years.

Demonstration of compliance with individual-protection standards for Yucca Mountain requires detailed, in-depth characterization of engineered and natural barriers and analysis of performance potential that assures a high degree of confidence in results presented for licensing reviews, and results that indicate that the predicted performance is substantially better than the required performance. As demonstrated clearly by Figure 3-2, current estimates of performance are significantly better than either the 25 mrem/yr standard or the 15 mrem/yr standard, and there is no need for increased costs for design improvements or data acquisition to demonstrate compliance with the 15 mrem/yr standard in comparison with the 25 mrem/yr standard. Indeed, it can be argued that adoption of the EDA II design, with an incremental cost of only $0.8 billion out of a total forward cost of nearly $22 billion (Section 3.8), is an effective time and cost saving strategy. It reduces the uncertainties and issues that were of concern for the VA design, and it improves the expected performance of the repository by several orders of magnitude, without facing the costs and time involved in trying to reduce uncertainties in the performance of the natural barriers, perhaps without definitive results. It can also be argued that more realistic treatment of juvenile waste package failures in the TSPA-VA, together with a relatively minor design change to switch the corrosion-resistant layer to the outside of the package, would by themselves have sufficiently improved performance. By this line of argument, the full change to the EDA II design may have been unnecessary, so that even a simply modified VA design may have been able to meet the IPS standards by orders of magnitude. In contrast to the several orders of magnitude improvement in performance for the EDA II design as shown in the TSPA-SR, the NRC and EPA individual-protection standards differ by less than a factor of two. The practical implication of this observation is that the proposed design can be expected to protect the public far better than is required by either of the slightly different standards.

6.2 Cost Impacts of the HIS Requirements

The standards for human intrusion, a performance standard unique to long-term geologic disposal, are the same as those for the IPS. All parties to evaluation of factors important to this demonstration of compliance concur with the NAS finding that a stylized scenario of intrusion and its consequences is needed because circumstances of intrusion cannot be predicted on the basis of scientific evidence. Therefore, the issues to be addressed in licensing reviews and compliance evaluations are:

- whether the intrusion scenario considered for licensing is reasonable, and
- what are the dose consequences of the appropriate scenario.

The EPA's standard for individual exposure limits for human intrusion (15 mrem/yr) is no different from the individual exposure limits applicable to gradual processes that will eventually degrade the repository's functional capability. Protection of human health is independent of the means by which it might be threatened. It is therefore appropriate and necessary for the EPA to prescribe that the standard for human intrusion be no different than that for the RMEI under undisturbed performance of the repository. The EPA is concerned only with the fact that individuals potentially affected by human intrusion be protected to the same extent as others. Details of the stylized intrusion scenario given in the rule are based on the recommendations of the NAS to EPA for the rulemaking (NAS95). EPA has adopted those recommendations it agrees with, to make clear to DOE and NRC the intent of the standard. However, EPA has not prescribed the scenario in excessive detail, thus allowing DOE and NRC to exercise their appropriate roles as applicant and regulator in implementing the EPA standard. Considerable flexibility has been left in the standard to explore the effects of alternative processes associated with releases from the repository and transport through natural barriers.

As discussed above, it is apparent that the HIS requirements have no impact on the costs of the DOE program for Yucca Mountain because, in fact, they are no different than the IPS requirements, as should be the case (i.e., protection is independent of the circumstances that require protection). Program schedules and costs for DOE have been established on the basis that demonstration of compliance with the IPS is needed and crucial; demonstration of compliance with HIS requirements can be developed independently through the intrusion scenario characteristics accepted for the basis for licensing reviews. Parameter values needed for the HIS analyses are available either from the parameters used in the IPS analyses, or may be based on straightforward assumptions without the need to collect additional field or laboratory data, as shown in Table 6-1.

Table 6-1. Data and Analysis Requirements for Assessing Compliance With the Human-Intrusion Standard

Data/Analysis Requirement	Source of the Information
Nature of the intrusion to be modeled	Defined in the standard: waste package penetration by water well drilling with current technology; connection to the saturated zone
Probability of the intrusion	Defined as unity (1.0) in the standard
Time frame for the intrusion	Derived from corrosion modeling done for the IPS assessments
Mechanism for release of radionuclides from the penetrated waste package: • direct fall down borehole • leaking package or diffusion release	Assumptions for the analysis; no testing required
Transport of radionuclides through the saturated zone to the compliance point	Required to use the same methods as for the IPS assessments
Doses to the receptor: • definition of the receptor • path through the biosphere	Same definition and analyses as for the IPS assessments

The key point is that the EPA standard is designed to assure that future populations are afforded the same protection as present populations. DOE programs and projected costs have been developed on the basis of the Department's expectations with regard to general licensing review requirements for demonstration of compliance with applicable standards. They have not been based on an assessment of the impact of compliance with specific regulatory standards.

TSPA-SR estimates of the impact of inadvertent human intrusion to be about 3 orders of magnitude below the standard, as shown in Figure 3-3. Differences are negligible between the proposed NRC approach to assume intrusion at 100 years, and the reasonable expectation approach, which would suggest that the waste package will be identifiable for much longer times. It can be concluded that neither the HIS requirement nor its timing have any impact on repository cost.

Data and analysis requirements for assessing compliance with the human-intrusion standard, which fall within the framework of requirements for assessing compliance with the individual protection standard, are summarized in Table 6-1. From this table, it is apparent that parameters and data necessary to analyze exposures are either defined in the rule or are already available from the IPS assessments. Consequently, no additional demands for data collection are imposed by the HIS. As a result, no additional significant program costs are imposed by the HIS requirements.

6.3 Cost Impact of the GWS Requirements

The Ground Water Protection Standards do not impose any additional costs on the program. The information required to evaluate compliance with the GWS is radionuclide concentration in the ground water as a function of distance from the repository. This is the same information as is required for assessment of compliance with the IPS, and no incremental costs or effort to assess ground water concentrations with a higher degree of certainty for the GWS in comparison with the IPS is appropriate or necessary. As shown in Figure 3-2, the GWS is of the same order of magnitude as the IPS, and the characteristics of the database that are needed for licensing reviews are the same for the GWS and the IPS.

As shown in Figures 4-1 and 4-2, the TSPA-SR analysis indicates no potential for impact of the GWS within the performance period, as there are no releases in the nominal scenario during this period. As noted in Section 4.2, concentrations were calculated in the period out to 100,000 years to demonstrate that no significant degradation occurs even after the 10,000-year time period is ended.

Data and analysis requirements for assessing compliance with the ground water protection standards are summarized in Table 6-2.

Table 6-2. Data and Analysis Requirements for Assessing Compliance With the Ground Water Protection Standards

Data/Analysis Requirement	Source of the Information
Water flux through the unsaturated zone above and into the repository (precipitation, infiltration, seepage into drifts, etc.)	Characterization data, models, and analyses for the IPS compliance evaluations
Source term for radionuclide releases from the repository (container failure profiles, exposed waste form areas, radionuclide leach rates, solubilities, etc.	Engineered barrier system characterization, testing and modeling as required for the IPS compliance evaluations
Characterization of saturated zone flow and radionuclide transport (hydroponic conditions down-gradient to the compliance point; only average values are required by the GWS)	Characterization data, flow and transport models, and analysis of the type required by the IPS compliance evaluations, but GWS requires less detail
Methods for calculating radionuclide concentrations in the Representative Volume	Methods defined in the standard; no further effort required

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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8.0 REFERENCES

AEA54	*Atomic Energy Act*, Public Law 83-703, as amended, 42 USC 2011 et seq., 1954.
BER92	Bernard, R.W. et al., *TSPA 1991: An Initial Total System Performance Assessment for Yucca Mountain*, SAND91-2795, Sandia National Laboratories, July 1992.
BOD97	Bodvarsson, G.S., Bandurraga, T.M., and Wu, Y.S., editors, *The Site-Scale Unsaturated Zone Model of Yucca Mountain, Nevada, for the Viability Asessment*, LBNL-40376, Berkeley, California, 1997.
DAG97	D'Agnese, F.A., Faunt, C.C., Turner, A.K., and Hill, M.C., *Hydrogeologic Evaluation and Numerical Simulation of the Death Valley Regional Ground Water Flow System, Nevada and California*, Water-Resources Investigations Report 96-4300, U.S. Geological Survey, 1997.
DOE86	U.S. Department of Energy, *Issues Hierarchy For A Mined Geologic Disposal System*, DOE/RW-0101, September, 1986.
DOE88	*Site Characterization Plan - Overview: Yucca Mountain Site, Nevada Research and Development Area, Nevada*, DOE/RW-0198, U.S. Department of Energy, December 1988.
DOE88a	*Site Characterization Plan, Yucca Mountain Site, Nevada Research and Development Area, Nevada*, DOE/RW-0199, U.S. Department of Energy.
DOE94	*Total System Performance Assessment - 1993: An Evaluation of the Potential Yucca Mountain Repository*, B00000000-0717-2200-0099-Rev. 01, Prepared by R.W. Andrews et al. INTERA, Inc., March 1994.
DOE95	*Total System Performance Assessment - 1995: An Evaluation of the Potential Yucca Mountain Repository*, B00000000-01717-2200-00136, Rev. 01, prepared by TRW Environmental Safety Systems Inc., November 1995.
DOE97	*Unsaturated Zone Flow Model Expert Elicitation Project*, CRWMS M&O Contractor, Las Vegas, Nevada, 1997.

DOE98 *Viability Assessment of a Repository at Yucca Mountain, Volume 3 - Total System Performance Assessment*, DOE/RW-0508, U.S. Department of Energy, December 1998.

DOE98a *Total System Performance Assessment - Viability Assessment (TSPA-VA) Analyses Technical Basis Document*, B00000000-01717-4301-00005 REV 01, U.S. Department of Energy, November 13, 1998.

DOE99 *Draft Environmental Impact Statement for a Repository at the Yucca Mountain Site, Nye County, Nevada*, U.S. Department of Energy, DOE/RW-0250D, August 1999.

DOE99a U.S. Department of Energy, *Yucca Mountain Site Suitability Guidelines*, 64 Federal Register 67054-67089, November 30, 1999.

DOE00 U.S. Department of Energy, *Dike Propagation Near Drifts*, Analysis/Model Report ANL-WIS-MD-000015 Rev 00, April 2000.

DOE00a U.S. Department of Energy, *Characterize Framework for Igneous Activity at Yucca Mountain, Nevada*, Analysis/Model Report ANL-MGR-GS-000001 Rev 00, June 2000.

DOE01 U.S. Department of Energy, *Yucca Mountain Science and Engineering Report, Technical Information Supporting Site Recommendation Consideration*, DOE/RW-0539, May 2001.

DOE01a U.S. Department of Energy, *Analysis of the Total System Life Cycle Cost of the Civilian Radioactive Waste Management Program*, DOE/RW-0553, May 2001.

EDD01 Eddebborh, Al.A., *What is the Mean and Variance of Transport Time of a Conservative Species in the SZ*, Handout for Presentation to the Nuclear Waste Technical Review Board Meeting, January 30-31, Amargosa Valley, Nevada, 2001.

EnP92 *Energy Policy Act of 1992*, Public Law 102-486, October 24, 1992.

EPA76 U.S. Environmental Protection Agency, *National Interim Primary Drinking Water Regulations*, EPA 50/9-76-003, 1976.

EPA85 U.S. Environmental Protection Agency, *Final Rule, Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level, and Transuranic Radioactive Wastes*, Federal Register, 50 FR 38066-38089, September 19, 1985.

EPA91 U.S. Environmental Protection Agency, 40 CFR Parts 141 and 142, *Proposed Rule, National Primary Drinking Water Regulations; Radionuclides*, Federal Register, 56 FR 33050, July 18, 1991.

EPA93 U.S. Environmental Protection Agency, 40 CFR Part 191, *Environmental Radiation Protection Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level, and Transuranic Radioactive Wastes*; *Final Rule*, Federal Register, 58 FR 66398-66416, December 20, 1993.

EPA99 U.S. Environmental Protection Agency, 40 CFR Part 197, *Environmental Radiation Protection Standards for Yucca Mountain, Nevada*; *Proposed Rule*, Federal Register, 64 FR 46976-47016, August 27, 1999.

EPA01 U.S. Environmental Protection Agency, 40 CFR Part 197, *Public Health and Environmental Radiation Protection Standards for Yucca Mountain, Nevada*; *Final Rule*, Federal Register, 66 FR 32074-32135, June 13, 2001.

EPR00 Electric Power Research Institute, *Evaluation of the Candidate High-Level Waste Repository At Yucca Mountain Using Total System Performance Assessment, Phase 5*, EPRI Report 1000802, November 2000.

FAB98 Fabryka-Martin, J.T. et al., *Distribution of Fast Hydrologic Paths in the Unsaturated Zone at Yucca Mountain*, Proceedings of the Eighth Annual Conference on High-Level Radioactive Waste Management, American Nuclear Society, May 11-14, 1998.

FLI96 Flint, A.L., Hevesi, J.A., and Flint, L.E., *Conceptual and Numerical Model of Infiltration for the Yucca Mountain Area*, U.S. Geological Survey, 1996.

GEO98 Geomatrix Consultants Inc. and TRW, *Saturated Zone Flow and Transport Expert Elicitation Project*, January 1998.

ICR77 International Commission on Radiation Protection, *Recommendations of the International Commission on Radiation Protection, ICRP Publication 26*, Pergamon Press, Oxford, 1977.

KOZ97 Kozak, M.W., *Sensitivity, Uncertainty, and Importance Analyses*, Proceedings of the 18th Annual Department of Energy Low-Level Radioactive Waste Management Conference, May 20-22, Salt Lake City, 1997.

NAS95 National Academy of Sciences, *Technical Bases for Yucca Mountain Standards, Committee on Technical Bases for Yucca Mountain Standards*, National Research Council, National Academy Press, 1995.

NIX70 The White House, President R. Nixon, *Reorganization Plan No. 3 of 1970*, Federal Register, 35 FR 15623-15626, October 6, 1970.

NRC99 U.S. Nuclear Regulatory Commission, *Disposal of High-Level Radioactive Wastes in a Proposed Geological Repository at Yucca Mountain, Nevada; Proposed Rule*, 64 Federal Register 8640-8679, February 22, 1999.

NRC99a U.S. Nuclear Regulatory Commission, *Issue Resolution Status Report, Key Technical Issue: Igneous Activity*, Revision 2, July 1999.

NWP83 *Nuclear Waste Policy Act of 1982*, Public Law 97-425, January 7, 1983.

NWP 87 *Nuclear Waste Policy Amendments Act of 1987*, Public Laws 100-202 and 100-203, December 22, 1987.

NYE00 N. Stellavato, *Nye County Drilling: Phase 2*, Presentation at the January 25-26, 2000 meeting of the Nuclear Waste Technical Review Board, Las Vegas, Nevada.

PRP99 Total System *Performance Assessment* Peer Review Panel, *Final Report*, February 11, 1999.

SCA99 S. Cohen & Associates, Inc, *Effectiveness of Fuel Rod Cladding as an Engineered Barrier in the Yucca Mountain Repository*, December 1999.

SCA00 S. Cohen & Associates, Inc., *Characterization and Comparison of Alternate Dose Receptors for Individual Radiation Protection for a Repository at Yucca Mountain*, April 2000 (Docket No. A-015-12, V-B-3).

TRB96 U.S. Nuclear Waste Technical Review Board, *Report to the U.S. Congress and The Secretary of Energy*, January to December 1996.

TRB99a DOE Presentations to the Nuclear Waste Technical Review Board, June 29-30, 1999, Beatty, Nevada.

TRB99b DOE Presentations to the Nuclear Waste Technical Review Board, September 14-15, 1999, Alexandria, Virginia.

TRB00a Stuckless, J., *Natural Analog Studies*, Presentation at the January 25-26, 2000, meeting of the Nuclear Waste Technical Review Board, Las Vegas, Nevada.

TRB00b Bodvarrson, G.S., *Application of Principal Factors: Seepage Studies*, Presentation at the January 25-26, 2000, meeting of the Nuclear Waste Technical Review Board, Las Vegas, Nevada.

TRW00 TRW Environmental Safety Systems, Inc., *Repository Safety Strategy: Plan to Prepare the Postclosure Safety Case to Support Yucca Mountain Site Recommendation and Licensing Considerations*, TDR-WIS-RL-000001 Rev 03, January 2000.

TRW00a TRW Environmental Safety Systems, Inc., *Total System Performance Assessment for the Site Recommendation,* TDR-WIS-PA-000001 REV 00 ICN 01, December 2000.

USC87 United States Court of Appeals for the First Circuit, *Natural Resources Defense Council Inc., et al., v. United States Environmental Protection Agency*, Docket No.: 85-1915, 86-1097, 86-1098, Amended Decree, September 23, 1987.

WIL94 Wilson, Michael et al., *Total System Performance Assessment for Yucca Mountain - SNL Second Iteration (TSPA-1993)*, Sandia National Laboratories, April 1994.

– – Editorial Changes to Docket Version – –

The following changes to the EIA in the Yucca Mountain Rule Docket (A-95-12, V-B-2) were made in this document to correct typographical and other minor errors in the text.

P. i — Item 1.1 changed to read, "EPA Action and Authority"
Item 1.7 changed to read , "Final 40 CFR Part 197 - Public Health and Environmental Radiation Protection Standards for Yucca Mountain, Nevada"

P. ii — Item 4.1 changed to read, "Performance in Comparison with the Individual-Protection Standards"
Item 4.2 changed to read, "Performance in Comparison with the Ground Water Protection Standards"

P. iv — Titles for Tables 3.6 and 3.7 added to the Table of Contents, existing Table 3.7 renumbered as 3.8.

Figure ES-1 changed to read, "Comparison of Radiation Protection Standards with Expected Values of TSPA-SR Calculations for a Repository at Yucca Mountain for Nominal and Igneous Scenarios"

P. v — Acronym OCRWM (Office of Civilian Radioactive Waste Management) added

P. 1-1 — Changed first sentence in subsection 1.1 to read, "The U.S. Environmental Protection Agency ...... has issued a rule....."

P. 1-2 — Changed the third sentence in subsection 1.3, paragraph 1, to read, "The regulation contains site-specific environmental standards....."

P. 1-11 — Changed the subsection heading to read, "Final 40 CFR Part 197 - Public Health and Environmental Radiation Protection Standards for Yucca Mountain, Nevada."

P. 1-12 — Changed the reference designation in subsection 1.7.1 italicized text to read (EPA01).

P. 1-13 — Inserted the word "proposed" in the first sentence below the first bulleted text in subsection 1.7.2, before the text "...§197.26"

Changed the first sentence after the second bulleted text to read, "In the final rule, EPA selected this second alternative in which DOE must project...."

P. 1-14 Modified the final sentence of the first paragraph of subsection 1.7.3 to read, "However, it is Agency policy, as well as national policy and the policy of many states, to protect ground water resources."
Deleted the sentence that begins, "If revised MCLs are promulgated.....", and the concluding sentence to the paragraph.

P. 1-15 Revised the italicized text to match the regulatory text in §197.30 of the final rule.

P. 1-16 Revised the italicized text to match the regulatory text in §197.21 of the final rule.

P. 1-18 Changed the first sentence of the second paragraph to read, "Another alternative RV proposed was 120 acre-ft/yr."

P.1-19 Deleted "has" from the first sentence of the second paragraph.
Corrected the reference (EPA99) to read "(EPA99, 01)."
Modified the second paragraph, last sentence to read "...portion of the Town of Amargosa Valley..."

P.3-33 In the second paragraph of subsection 3.7.1.3, changed "draft 40 CFR part 197" to read "proposed 40 CFR Part 197".

P. 3-37 In the first sentence of paragraph one of Section 3.8, changed the text to reference Table 3-8, rather than 3-7.

P. 3-39 Table 3-7 changed to Table 3-8; Item 4 total cost corrected to 35.4 from 36.3;
Item 6 revised to read, "Total Repository Cost (1983-2119)";
Item 7 revised to read, " Total Program Cost"

P. 4-3 Changed 20 km to 18 km.

P. 5-1 Modified the last sentence of the second paragraph of Section 5.1 to read, "Reasonable assurance is a concept that has been used...."

P. 5-2 Inserted the reference designation "(EPA99)" in the second paragraph, first sentence

P. 6-4 Changed paragraph two, second sentence to read, "...with regard to general licensing review requirements.... with applicable standards."
Changed paragraph two, last sentence to read, "...on an assessment of the impact of compliance with specific EPA regulatory standards."

P. 8-3 Added reference to EPA final standards (EPA01)

Deleted the word "proposed" from the following text locations which refer to the final rule:

P. ES-3, Figure ES-1 (and added proposed to the line "NRC proposed 25 mrem/yr IPS Limit"); p. 1-1, section 1.1 text and heading and subsection 1.2; p. 1-2, subsection 1.3, first sentence; p. 1-9, first paragraph; p. 3-39 (Figure 3-2); p. 3-37, second paragraph, last sentence - inserted "the relevant"; p. 4-1, heading for Section 4.1; p. 4-2, second paragraph, 4 th sentence; p. 4-3, second paragraph, first sentence, and the heading for section 4.2; p. 4-16, paragraph two, last sentence; p. 4-17, paragraph one, first sentence; p. 5-1, section 5.1 - second paragraph, first sentence; p.5-2, first paragraph, first two sentences; p. 5-3, second paragraph, first sentence; p. 6-1, paragraph four, last sentence and inserted the word "selected; p. 6-3, second to last sentence of paragraph one, the first sentences of paragraphs two and three; p. 6-4, first sentence of paragraph two; p. 7-1, first sentence of the text in bulleted texts; p. 7-3, second sentence of paragraph two; p. 7-5, first sentence of paragraph two and inserted the word "proposed" before "NRC regulations."