# Appendix B

# Postclosure Safety Review for a Potential Repository at Yucca Mountain (Key References and Context)

## Table of Contents

# Introduction - Postclosure Safety (SER Volume 3)

Volume 3 of the staff's Safety Evaluation Report (SER) (NRC 2014) documents the staff's review of DOE's license application to determine whether the proposed repository design complies with the performance objectives and requirements that apply after the repository is permanently closed. Volume 3 of the SER stated:

> *"The NRC staff finds, with reasonable expectation, that DOE has demonstrated compliance with the NRC regulatory requirements for postclosure safety, including, but not limited to, "Performance objectives for the geologic repository after permanent closure" in 10 CFR 63.113, "Requirements for performance assessment" in 10 CFR 63.114, "Requirements for multiple barriers" in 10 CFR 63.115, and "Postclosure Public Health and Environmental Standards" in 10 CFR Part 63, Subpart L. In particular, the NRC staff finds that the proposed repository at Yucca Mountain (1) is comprised of multiple barriers and (2) based on performance assessment evaluations that are in compliance with applicable regulatory requirements, meets the 10 CFR Part 63, Subpart L limits for individual protection, human intrusion, and separate standards for protection of groundwater."* (Volume 3 of SER, page vii)

The NRC staff's evaluation; consistent with the risk-informed, performance-based regulations at 10 CFR Part 63 and the Yucca Mountain Review Plan (YMRP); considered the proposed geologic repository's multiple barriers, both natural and engineered (manmade); and the performance assessments (including model abstractions) used for the individual protection, the separate groundwater protection, and the human intrusion evaluations. Key aspects of the review are described below for the (1) multiple barriers; (2) features, events and processes considered for the performance assessment; and (3) models, assumptions, and parameters in the performance assessment used for demonstrating compliance with the quantitative limits for individual protection, separate groundwater protection, and human intrusion.

The NRC evaluation considered an initial period of 10,000 years after closure and the period after 10,000 years but within the period of geologic stability (i.e., specified as 1,000,000 years at § 63.302). The regulatory requirements vary between these two time periods based, in part, due to variation in the Environmental Protection Agency's (EPA's) standards for these two time periods that account for uncertainties in making assessments for such long time periods (federal register notices describe EPA's final standards for the initial 10,000 years [EPA 2001] and NRC's implementation for this initial period [NRC 2001 and 2002]; and EPA's final standards for the time period after 10,000 years [EPA 2008] and NRC's implementation for this longer time period [NRC 2009]).

Key aspects of NRC's requirements for the period after 10,000 years up to 1,000,000 years specify that:

- Support for models for the initial 10,000 years is considered appropriate for the period after 10,000 years [§ 63.114(b)]

- Performance assessment for the period beyond 10,000 years has specific requirements for the inclusion of certain features, events, and processes in the performance assessment and specific limits for the post 10,000 year assessment period, in particular § 63.342(c) specifies:

- The seismic analysis may be limited to the effects caused by damage to the drifts in the repository, failure of the waste packages, and changes in the elevation of the water table under Yucca Mountain (i.e., the magnitude of the water table rise under Yucca Mountain).

- The igneous activity analysis may be limited to the effects of a volcanic event directly intersecting the repository. The igneous event may be limited to that causing damage to the waste packages directly, causing releases of radionuclides to the biosphere, atmosphere, or ground water.

- DOE must assess the effects of climate change. The climate change analysis may be limited to the effects of increased water flow through the repository as a result of climate change, and the resulting transport and release of radionuclides to the accessible environment. The nature and degree of climate change may be represented by constant-in-time climate conditions. The analysis may commence at 10,000 years after disposal and shall extend through the period of geologic stability. The constant-in-time values to be used to represent climate change are to be the spatial average of the deep percolation rate within the area bounded by the repository footprint. The constant-in-time deep percolation rates to be used to represent climate change shall be based on a lognormal distribution with an arithmetic mean of 41 mm/year (1.6 in./year) and a standard deviation of 33 mm/year (1.3 in./year). The lognormal distribution is to be truncated so that the deep percolation rates vary between 10 and 100 mm/year (0.39 and 3.9 in./year).

- DOE must assess the effects of general corrosion on engineered barriers. DOE may use a constant representative corrosion rate throughout the period of geologic stability or a distribution of corrosion rates correlated to other repository parameters.

• The annual dose limit for the period after 10,000 years is 1.0 mSv (100 mrem) as specified at § 63.321(b)(2).

This appendix is organized according to the sections that make up the post-closure volume (Volume 3 of NUREG 1949) of the staff's Safety Evaluation Report (SER). In particular the numbered sections in this report mirror the numbers and titles of the Volume 3 of the SER. Additionally, the references cited in these sections make use of the same reference structure (e.g., DOE 2009aj) that is used in the SER to assist readers that going between this appendix and the SER.

The first section of this report provides an overview of the multiple barriers DOE identified and supported in its license application. The capabilities of the multiple barriers that DOE described that the safety of the repository relies upon provides the foundation for risk-informing the review, as those items most important to safety were identified. The multiple barriers section provides a more detailed discussion of DOE's approach than that provided in the remaining sections that discuss specific aspects of the review (e.g., climate and infiltration, degradation of engineered barriers, biosphere characteristics).

The issue specific sections (sections 2 thru 20) each contain four similar subsections (i.e., regulatory requirements unique for the specific issue, performance perspectives for the specific issue, key topics of the review of the specific issue, and references specific to the issue). It is important to recognize that this document provides a roadmap for putting into context and identifying keys aspects of the post-closure review – it is not intended to replace the SER, which is the key document for preparation of expert testimony and participation in any future licensing hearing for a potential repository at Yucca Mountain. This document is intended to serve as a 'roadmap' to help focus staff, new to the repository program, in understanding the repository program for high-level waste disposal based on perspectives and knowledge of staff that participated in the review and development of the SER for Yucca Mountain.

This report does not re-interpret or revise the SER – this report utilizes direct quotes from the SER (identified in most cases by indented and italicized text for easy identification) to utilize to the maximum extent possible the staff's review as documented in the SER.

## Generic References

(Note: Generic references relevant to all 20 Sections are provided here to avoid repetition in all 20 Sections)


Federal Register Notices regarding EPA Standards and NRC Regulations

EPA 2008; 40 CFR Part 197 – Public Health and Environmental Radiation Standards for Yucca Mountain, Nevada; Final Rule; U.S. Environmental Protection Agency, Washington, D.C; 73 FR 61256 61289; October 15, 2008.

EPA 2001; 40 CFR Part 197 – Public Health and Environmental Radiation Standards for Yucca Mountain; NV; Final Rule; U.S. Environmental Protection Agency, Washington, D.C; 66 FR 32074 - 32135; June 13, 2001.

NRC, 2014; NUREG-1949, Vol. 3, "Safety Evaluation Report Related to Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada; Volume 3: Repository Safety After Permanent Closure;" October 2014, ML14288A121, Washington, D.C.: U.S. Nuclear Regulatory Commission.

NRC 2009; 10 CFR Part 63 – Implementation of a Dose Standard After 10,000 Years; Final Rule; U.S. Nuclear Regulatory Commission; Washington, D.C.; 74 FR 10811 - 10830; March 13, 2009.

NRC 2002; 10 CFR Part 63 – Specification of a Probability for Unlikely Features, Events and Processes; Final Rule; U.S. Nuclear Regulatory Commission; Washington, D.C.; 67 FR 62629 - 62634; October 8, 2002.

NRC 2001; 10 CFR Part 63 – Disposal of High-Level Radioactive Wastes in a Proposed Geological Repository at Yucca Mountain, Nevada; Final Rule; U.S. Nuclear Regulatory Commission; Washington, D.C.; 66 FR 55732 - 55816; November 2, 2001.

DOE's Safety Analysis Report (SAR)

DOE. 2009av. DOE/RW–0573, "Yucca Mountain Repository License Application." Rev. 1. ML090700817, ML090710096. Las Vegas, Nevada: DOE, Office of Civilian Radioactive Waste Management.

DOE. 2008ab. DOE/RW–0573, "Yucca Mountain Repository License Application." Rev. 0. ML081560400. Las Vegas, Nevada: DOE, Office of Civilian Radioactive Waste Management.

NRC's Yucca Mountain Review Plan (YMRP)

NRC, 2003; NUREG-1804, "Yucca Mountain Review Plan—Final Report." Rev. 2; ML032030389; 2003; Washington, DC: U.S. Nuclear Regulatory Commission.

NRC's Safety Evaluation Report (SER)

NRC, 2010; NUREG-1949, Vol. 1, "Safety Evaluation Report Related to Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada; Volume 1: General Information;" August 2010, ML102440298, Washington, D.C.: U.S. Nuclear Regulatory Commission.

NRC, 2014; NUREG-1949, Vol. 3, "Safety Evaluation Report Related to Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada; Volume 3: Repository Safety After Permanent Closure;" October 2014, ML14288A121, Washington, D.C.: U.S. Nuclear Regulatory Commission.

NRC, 2014a; NUREG-1949, Vol. 4, "Safety Evaluation Report Related to Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada; Volume 4: Administrative and Programmatic Requirements;" December 2014, ML14346A071, Washington, D.C.: U.S. Nuclear Regulatory Commission.

NRC, 2015; NUREG-1949, Vol. 2, "Safety Evaluation Report Related to Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada; Volume 2: Repository Safety Before Permanent Closure;" January 2015, ML15022A146, Washington, D.C.: U.S. Nuclear Regulatory Commission.

NRC, 2015a; NUREG-1949, Vol. 5, "Safety Evaluation Report Related to Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada; Volume 5: Proposed Conditions on the Construction Authorization and Probable Subjects of License Specifications;" October 2014, ML15022A488, Washington, D.C.: U.S. Nuclear Regulatory Commission.

# 1.0 System Description and Demonstration of Multiple Barriers

The safety programs for geologic repositories throughout the world have, from the beginning, emphasized the need for a multiple barrier approach for disposal of high-level waste. The multiple barrier approach relies on both engineered barriers (e.g., such as a long-lived waste package) and natural barriers (e.g., geologic properties of the site that limit the contact of water with waste and geochemical properties of the host rock that slows the transport of radionuclides in the groundwater.

The Yucca Mountain Review Plan (YMRP) [NRC 2003aa] described how the review of barriers in the license application would be used to inform NRC's review of post-closure safety:

> *"The U.S. Department of Energy must identify the important barriers (engineered and natural) of the performance assessment, describe each barrier's capability, and provide the technical basis for that capability. This risk information describes the U.S. Department of Energy understanding of each barrier's capability to prevent or substantially delay the movement of water or radioactive materials. Staff review of the U.S. Department of Energy performance assessment—first the barrier analysis and later the rest of the performance assessment—considers risk insights from previous performance assessments conducted for the Yucca Mountain site, detailed process modeling efforts, laboratory and field experiments, and natural analog studies. The result of the initial multiple barrier review is a staff understanding of each barrier's importance to waste isolation, which will influence the emphasis placed on the reviews conducted in Sections 2.2.1.2, "Scenario Analysis and Event Probability" and 2.2.1.3, "Model Abstraction." The emphasis placed on particular parts of the staff review will change based on changes to the risk insights or in response to preliminary review results."*
> (YMRP, Revision 2; page 2.2-1)

NRC's multiple barrier requirements at § 63.115 require DOE to (a) identify those design features of the engineered barrier system and natural features of the geologic setting that are considered barriers important to waste isolation, (b) describe the capability of the barriers to isolate waste, and (c) provide the technical basis for the description of each barriers' capabilities. As defined at § 63.2 a barrier "prevents or substantially reduces the rate of movement of water or radionuclides from the Yucca Mountain repository to the accessible environment or prevents the release or substantially reduces the release rate of radionuclides from the waste." "A requirement that multiple barriers make up the repository system ensures that repository performance is not wholly dependent on a single barrier. As a result, the system is more tolerant of failures and external challenges such as disruptive events" [NRC 2001; 66 FR 55747, November 2, 2001].

NRC regulations at § 63.113 specify that "[T]he geologic repository must include multiple barriers, consisting of both natural barriers and an engineered barrier system." DOE has the flexibility to identify the barriers that it relies on for safety, however, the repository is required to have at least two barriers (i.e., multiple) and – one that is from the engineered barrier system (i.e. an engineered barrier) and one that is from the natural features of the geologic setting (i.e, a geologic barrier). DOE's Safety Analysis Report (SAR) explained:

> *"Multiple natural features of the Yucca Mountain site and engineered features of the repository design combine to form the following three barriers important to waste isolation: the Upper Natural Barrier, the EBS, and the Lower Natural Barrier. The Upper Natural Barrier includes the geologic units from the surface to the repository horizon, including alluvial soils and gravel, the Tiva Canyon welded tuff, the Paintbrush nonwelded tuff, and the Topopah Spring welded tuff. The EBS is composed of the manmade features within the emplacement drifts, including the drip shield, waste package, waste form, and other engineered components. The Lower Natural Barrier includes the unsaturated and saturated volcanic tuff units below the repository and older bedrock units and alluvial deposits below the water table between Yucca Mountain and the accessible environment in Amargosa Valley."* (DOE 2008ab, SAR, page 2-2)

The attributes of the multiple barriers provided a focus for the staff's review of DOE's multiple barriers, as well as, the review of key aspects of the features, events and processes considered for the performance assessment; model abstractions included in the performance assessment; and performance assessment results for individual protection, separate groundwater protection, and human intrusion. It is important to note that NRC specified in the regulations at § 63.115(c) that the technical basis for each barrier's capability shall be based on and consistent with the technical basis for the performance assessments used to demonstrated compliance with the individual protection standard after permanent closure and the separate standards for protection of ground water. As described previously, the NRC's staff approach for risk-informing its review is explained in the YMRP.

## 1.1 Multiple Barrier Descriptions and Capabilities

In its SAR for the proposed repository at Yucca Mountain, DOE identified three barriers: the Upper Natural Barrier, the Engineered Barrier System (EBS), and the Lower Natural Barrier

> *"The NRC staff's review of the description and technical basis for barrier capability is based on a list of 22 individual features presented in SAR Table 2.1-1. For purposes of evaluation, the NRC staff consolidated these features to yield nine features as shown in the second column of SER Table 1-1. The NRC staff consolidated the 22 barrier features because it found that several features in the second column of SAR Table 2.1-1 are related. For example, the emplacement drift is referred to twice. The NRC staff, therefore, consolidated the two emplacement drift entries into a grouped entry titled 'Emplacement Drift.' Also, 11 of the features listed in SAR Table 2.1-1 were prefaced with the term 'Waste Form and Waste Package Internals.' The NRC staff grouped all of these 11 features into 1 component titled 'Waste Form and Waste Package Internals.' The NRC staff included cladding into this grouped category because the cladding is a component that contains the waste form and is internal to the waste package. The NRC staff also noted that neither the emplacement pallet nor the invert was classified as important to waste isolation in SAR Table 2.1-1, and that both components serve to support the waste package. The NRC staff, therefore, consolidated these two features into a single barrier feature titled 'Emplacement Pallet and Invert.' The resulting consolidated list is consistent with the grouping that DOE used in SAR Section 2.1.2.2 in its summary of the features, processes, and characteristics of the engineered barrier system that are important to waste isolation."* (SER Vol. 3, page 1-4)

A summary description of each of the barrier components and the associated capabilities is provided below grouped by the three barriers identified by DOE (i.e., upper natural barrier, engineered barrier system, and the lower natural barrier). These summaries provide key aspects of the risk perspective used to assist in the review of post-closure safety. The NRC provided a complete discussion on multiple barriers in Section 2.2.1.1 “System Description and Demonstration of Multiple Barriers.”

Table 1-1 from the SER Vol. 3 (page 1-5):

**Table 1-1. Summary of NRC Staff’s Barrier Component Review**

| Barrier | Barrier Feature | SAR Table 2.1-1 ITWI* Components | SAR Table 2.1-1 Non-ITWI Components |
|---|---|---|---|
| Upper Natural Barrier | Topography and Surficial Soils | Topography and Surficial Soils | None |
| Upper Natural Barrier | Unsaturated Zone Above the Repository | Unsaturated Zone Above the Repository | None |
| Engineered Barrier System (EBS) | Emplacement Drift | Emplacement Drift | Emplacement Drift: Nonemplacement Openings, Closure, Ground Support, and Ventilation System |
| EBS | Drip Shield | Drip Shield | None |
| EBS | Waste Package | Waste Package | None |
| EBS | Waste Form and Waste Package Internals | • Transport, aging, and disposal (TAD) canister<br>• Naval canister<br>• Commercial spent nuclear fuel (SNF) and high-level waste glass<br>• Naval SNF<br>• Naval SNF canister System components†<br>• TAD canister internals†<br>• DOE SNF canister internals† | • DOE SNF canister<br>• High-level waste canister<br>• Codisposal package internals<br>• DOE SNF<br>• Cladding |
| EBS | Emplacement Pallet and Invert | None | • Waste Package Pallet<br>• Invert |
| Lower Natural Barrier | Unsaturated Zone Below the Repository | Unsaturated Zone Below the Repository | None |
| Lower Natural Barrier | Saturated Zone | Saturated Zone | None |

*ITWI stands for “important to waste isolation.”
†DOE identified these components as important to waste isolation solely in relation to their capability to reduce the probability of criticality.

### 1.1.1 Upper Natural Barrier

The Upper Natural Barrier is composed of two features above the repository (i.e., topography and surficial soils; and the unsaturated zone above the repository) that reduce the quantity and rate of movement of water downward toward the repository, which in turn reduces the rate of movement of water from the radioactive waste in the repository to the accessible environment.

**Upper Natural Barrier: Topography and Surficial Soils**

The topography and surficial soils provide a barrier capability to prevent or substantially reduce the rate of water movement.

> *"DOE's climate and infiltration analyses are summarized in SAR Tables 2.3.1-2, 2.3.1-3, and 2.3.1-4. DOE concluded in SAR Section 2.1.2.1.1 and in DOE (2009an, Enclosure 1) that for approximately 10,000 years following closure of the repository, a limited amount of water would infiltrate the unsaturated zone above the repository at Yucca Mountain. DOE attributed the low rate of infiltration to low precipitation that is substantially further reduced by high rates of evapotranspiration (e.g., uptake by plants, surface evaporation) and surface runoff. In SAR Section 2.1.2.1.1, DOE stated that the average net infiltration rate estimates range from about 3 to 17 percent of the total precipitation, depending upon the climate state and the infiltration scenario. For the post-10,000-year period, DOE stated that it used the deep percolation rate distribution specified in the proposed 10 CFR 63.342(c)(2) rule. In DOE (2009cb, Enclosure 6), DOE stated that use of the distribution of deep percolation specified in the final 10 CFR 63.342(c)(2) rule led to an insignificant increase in radiation dose."* (SER Vol. 3, page 1-7)

**Upper Natural Barrier: Unsaturated Zone Above the Repository**

The unsaturated zone above the repository provides a barrier capability to prevent or substantially reduce seepage.

> *"In SAR Section 2.1.2.1.6.2, DOE explained that the average percolation flux at the repository depth is, at most, a few percent less than the average net infiltration near the surface above the repository. Because changes in the flow rate of water between the ground surface and the repository level are relatively small, the NRC staff determines that DOE did not attribute barrier capability to any significant processes that result in the diversion of water away from the emplacement drift location. However, DOE explained in SAR Sections 2.1.2.1.2 and 2.1.2.1.6.2 and in DOE (2009an, Enclosures 1 and 2) that capillary diversion of water at the host rock–air interface at the drift wall prevents much of the water flowing in the rock at the repository level from entering the drift as seepage (i.e., dripping). DOE explained that at some drift locations, all of the water is diverted around the drift, resulting in no drips at all; at others, only some of the water enters, and the remainder is diverted around the drift. In addition, the short duration, relatively higher flow rates resulting from infiltration following brief episodes of precipitation are spread out in time and space as they pass through the Paintbrush Tuff. In DOE (2009an, Enclosure 2), DOE explained that this*

*damping of episodic infiltration pulses by the Paintbrush Tuff results in water flow rates below the Paintbrush Tuff that are consistently lower than the peak flow rate during the infiltration pulse, but which are more nearly constant over time (i.e., steady-state fluxes below the Paintbrush Tuff). DOE explained that because capillary diversion processes are more effective at low percolation flow rates, the damping of episodic infiltration pulses by the Paintbrush Tuff contributes to the effectiveness of the capillary barrier. DOE quantified the barrier capability of the unsaturated zone above the repository for each of the five percolation subregions for the climate states projected for the first 10,000 years after repository closure (SAR Section 2.1.2.1.2). DOE used an analysis based on the TSPA seepage models and inputs to demonstrate that average seepage rates range from less than 1 to about 17 percent of the percolation fluxes for intact drifts within the first 10,000 years following closure, as described in DOE (2009bo, Enclosure 3, Table 11). DOE expects capillary forces to divert more than 80 percent of percolation flux away from the intact drifts for the initial 10,000 years after closure. DOE (2009bo, Enclosure 3, Table 5) identified that for intact drifts, the fraction of the repository experiencing dripping conditions (i.e., the seepage fraction) ranges from 10 to 70 percent. Results for the collapsed drift case, which is a likely scenario in the post-10,000-year period, show that the mean seepage percentage ranges from about 40 to 56 percent, as described in DOE (2009bo, Enclosure 3, Table 11). DOE expects that capillary forces would divert at least 44 percent of percolation flux away from collapsed drifts. The post-10,000-year seepage fractions for the corresponding flow fields range from about 44 to 89 percent, as described in DOE (2009bo, Enclosure 3, Table 8).”* (SER Vol. 3, page 1-9)

### 1.1.2 Engineered Barrie System (EBS)

The EBS includes different engineering features (e.g., emplacement drifts, drip shields, waste packages and its internal components) important to waste isolation that are designed to (1) enhance the performance of the waste package, preventing radionuclide releases while it is intact; (2) limit radionuclide releases after the waste package is breached by limiting the amount of water that can contact the waste package, and (3) limit radionuclide release from the engineered barrier system through sorption processes. Delay of releases allows for radioactive decay to reduce the radioactive inventory.

**Engineered Barriers System (EBS): The Emplacement Drift**

The emplacement drift provides a barrier capability (e.g., capillary barrier) to prevent or substantially reduce the amount of water entering the emplacement drift and prevent or reduce the rate of movement of radionuclides out of the emplacement drift.

*“DOE discussed the barrier capabilities of the emplacement drift in SAR Section 2.1.2.2 under the discussion titled ‘Emplacement Drift’ and in DOE (2009an, Enclosures 1 and 3). DOE stated that the capability of the emplacement drift to prevent or substantially reduce the movement of water is associated with the capillary barrier discussed under the upper natural barrier in SAR Section 2.1.2.1. DOE associated the capability of the drift to prevent or reduce the rate of movement of radionuclides with the effect of temperature and water chemistry on various processes affecting the degradation of the other engineered barrier system (EBS) components (e.g., drip shield, waste package, and waste form) and*

*radionuclide transport. DOE (2009an, Enclosures 1 and 3) specifically identified and discussed the roles of individual processes in the capability of the emplacement drifts. The NRC staff finds that DOE has described the emplacement drifts capabilities as follows:*

- *The intact emplacement drift opening represents a zero-capillarity feature within the rock formation that supports diversion of unsaturated zone flow around the opening, which reduces the rate of seepage into the drift.*

- *The collapsed, rubble-filled emplacement drift provides reduced seepage diversion capabilities and limits drip shield and waste package motion under seismic activity.*

- *The mechanical integrity of the drift provides a stable environment that controls the mechanical and chemical degradation of the drip shield and waste packages, which divert seepage water and prevent or limit the rate of contact of water with the waste form.*

- *The mechanical integrity of the drift provides a stable environment that controls the rate of waste form degradation and the chemical conditions within the waste package, which control the rate of movement of radionuclides."* (SER Vol. 3, page 1-11)

## <u>Engineered Barriers System: The Drip Shield</u>

The drip shield provides a barrier capability to prevent or substantially reduce contact of seepage with the waste package.

*"DOE discussed the capability of the drip shield to prevent or substantially reduce contact of seepage with the waste package in SAR Section 2.1.2.2 under the discussion titled 'Drip Shield,' in SAR Section 2.1.2.2.1, and quantitatively in SAR Section 2.1.2.2.6. DOE supplemented its discussion in DOE (2009an, Enclosure 1). DOE addressed the drip shield's capability to prevent seepage water from contacting the waste package during the thermal period in SAR Section 2.1.2.2. The thermal period is the time period when the temperature of the host rock and EBS are above the ambient temperature of the host rock (SER Section 2.2.1.3.6). During the thermal period, seepage water, if contacting the waste package, could lead to water chemistry that may initiate localized corrosion.*[1]

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*DOE does not expect extensive drip shield failures before 100,000 years. General corrosion of the drip shield enhances the vulnerability of the drip shield to seismic events as the drip shield plates become thinner as a result of corrosion. DOE expects drip shields to fail between 200,000 and 300,000 years, when general corrosion has weakened the drip shield plates sufficiently such that a seismic event can rupture them. DOE attributes the capability of the drip shield to divert water to corrosion-resistant materials coupled with a low*

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[1] Boiling and recirculation of water during the thermal period may result in the buildup of salts and modification of ambient chemistry.

*probability of mechanical damage from seismic events and a relatively benign chemical environment during the thermal period."* (SER Vol. 3, page 1-13)

## Engineered Barriers System: The Waste Package

The waste package provides a barrier capability to prevent or substantially reduce the contact of seepage with the waste form.

*"In SAR Section 2.1.2.2, DOE attributed the capability of the waste package to divert water to corrosion-resistant materials coupled with a low probability of mechanical damage from seismic events and a relatively benign chemical environment. DOE discussed the incidence of waste package failure and concluded that extensive early failures of the waste packages are unlikely. DOE does not expect extensive waste package failures to occur until a seismic event capable of damaging the waste packages occurs. Although a model for localized corrosion is included in the TSPA analysis, DOE expects that the presence of the drip shields over the entire thermal period will prevent the occurrence of localized corrosion under the nominal or seismic scenarios. DOE indicated that waste package failures before approximately 200,000 years are primarily due to seismically induced stress corrosion cracking of codisposal waste packages containing DOE standard canisters and high-level waste. DOE attributed the higher resilience of the commercial spent nuclear fuel waste packages under seismic conditions, relative to the codisposal packages, to the damping provided by the massive transport, aging, and disposal canister containing the commercial spent fuel. DOE stated that upon failure of the drip shield and filling of the drift with rubble, damage from further seismic events is unlikely. DOE also stated that subsequent failures are largely associated with nominal processes affecting both commercial spent nuclear fuel waste packages and codisposal waste packages. Under nominal conditions, DOE expects approximately 50 percent of both the commercial spent nuclear fuel and codisposal waste packages to fail by stress corrosion cracking by 1 million years. DOE predicted that the earliest general corrosion waste package failure (at the 95th percentile) would occur at 560,000 years. At 1 million years, about 10 percent of the waste packages are predicted to fail from general corrosion.*

*The ability of a breached waste package to prevent or reduce water flow is dependent upon the type and extent of the failure. DOE modeled stress corrosion cracking breaches as allowing only diffusive release from the waste package. Larger breaches (primarily due to general corrosion and rarely due to rupture or puncture of the waste package during a seismic event) allow water flow, but a small breached area may limit the rate at which water may enter the waste package. DOE (2009an, Enclosure 4), based on the flux-splitting submodel documented in SAR Section 2.3.7.12.3.1, indicated that a waste package breached by general corrosion is still capable of significant water diversion provided that the breach area is limited to a small percentage of the waste package surface area."* (SER Vol. 3, page 1-14 and 15)

## Engineered Barriers System: Waste Form and Waste Package Internal Components

The waste form and waste package internal components provide a barrier capability by limiting the release of radionuclides from a failed waste package. For example, certain radionuclides have an affinity for sorbing onto the corrosion products (primarily from corrosion of the inner cannister) and thus will be retained within the waste package outer corrosion resistant container.

*"DOE provided a qualitative description of how the waste form and waste package internal components limit the release of radionuclides from a failed waste package in SAR Section 2.1.2.2 under the discussion titled 'Waste Form and Waste Package Internals,' in SAR Section 2.1.2.2.2, and in DOE (2009an, Enclosures 1 and 5). DOE described the performance of the waste package internal components quantitatively in SAR Section 2.1.2.2.6. DOE discussed the impacts of these processes in an aggregated fashion, using a metric that indicates the extent to which radionuclides are retained within the entire engineered system over time. Specifically, the approach identifies, for selected radionuclides, the decayed cumulative release from the engineered system (this means, the amount of radionuclides existing within either the lower natural barrier or the accessible environment relative to the total inventory in the entire system). The capabilities DOE described are consistent with the definition of a barrier at 10 CFR 63.2 because DOE described a capability to substantially reduce the rate of release and movement of radionuclides from the waste package.*

*DOE attributed the barrier capability of the waste form and waste package internal components to a number of significant processes that can affect release rates. These processes include waste form degradation, precipitation and dissolution, colloid generation and stability, and sorption to and desorption from waste package internal components. These processes are in turn affected by the chemistry of the aqueous solution inside the failed waste packages as well as the water flow rate within the package. DOE described how these processes limit releases from the engineered barrier system and how these processes are associated with the different internal components of the waste package in DOE (2009an, Enclosures 1 and 5). NRC staff found that DOE provided the following information:*

- *DOE (2009an, Enclosure 1) provided a discussion of the relationship between specific processes and the safety classification of individual waste form and waste package internal components. For example, DOE explained that it considers the waste package inner vessel to be the dominant source of corrosion products for corrosion product sorption, and that corrosion of other internal components is not as significant and is therefore not considered important to waste isolation.*

- *DOE provided specific information on the rate at which waste forms degrade in DOE (2009an, Enclosure 5, Section 1.1). DOE provided calculations based on TSPA model input parameters that evaluate mean waste form lifetimes on the order of up to a few thousand years for spent fuel and tens to hundreds of thousands of years for high-level waste glass waste forms, as identified in DOE (2009an, Enclosure 5, Tables 1.1-1 and 1.1-2). Based on the DOE results provided in DOE (2009an, Enclosure 5, Tables 1.1-1 and 1.1-2), the high-level waste glass waste form lifetime is significantly more uncertain, with waste form lifetimes that can range anywhere from a few hundred years to over 100 million years.*

- *DOE discussed in DOE (2009an, Enclosure 5, Section 1.2), on the basis of a selection of TSPA model realizations, the effectiveness of the limited breach area associated with cracks for retaining radionuclides under diffusive release conditions, and demonstrated that the effect of breach area on release depends on the nuclide and the magnitude of the breach area. DOE concluded that for soluble nuclides, releases are sensitive to the breach area for low breach area fractions, but become insensitive to the breach area as the breached area approaches just a few hundred square millimeters. For sorbing, solublility-limited nuclides, DOE concluded that the sensitivity persists for higher breached areas.*

- *DOE (2009an, Enclosure 5, Sections 1.3 and 1.4) discussed, on the basis of sensitivity analyses and selected TSPA model realizations, the effectiveness of solubility limits and sorption to corrosion products for limiting the releases from the waste package. DOE observed that for the relatively insoluble, sorbing nuclides such as Np-237 and Pu-242, both precipitation/dissolution processes and sorption onto corrosion products are significant in limiting releases from the engineered barrier system.*

- *DOE addressed the significance of colloidal processes in DOE (2009an, Enclosure 5, Section 1.5). DOE does not identify transport facilitated by colloidal suspensions as significant to the barrier capability of the waste form and waste package internal components. DOE explained that colloids do not facilitate significant releases relative to dissolved forms of the same radionuclides."* (SER Vol. 3 pages 1-17 and 18)

## Engineered Barriers System: Emplacement Pallet and Invert

DOE did include the emplacement pallet and invert as part of descriptions of the barriers, however, DOE did not consider these items to be important to waste isolation (SER Volume 3 page 1 19). DOE described that these barrier's capabilities were either not included in the performance assessment or did not make a significant contribution to performance. In particular:

> *"DOE identified a potential barrier capability of the emplacement pallet to reduce diffusive releases from the engineered barrier system by preventing contact between the waste package and invert, thereby reducing diffusive releases, but explained that this capability was not included in the TSPA model."* (SER Volume 3, page 1-19)
>
> *"DOE explained that the invert contributes to barrier capability because low diffusion rates and potential sorption of radionuclides in the crushed tuff ballast slow the release rate of radionuclides from the waste package to the unsaturated rock beneath the drift. However, DOE determined that the delaying effect in the invert is not significant over long time frames, so DOE classified the invert as not important to waste isolation."* (SER Volume 3, pages 1-20)

### 1.1.3 Lower Natural Barrier

The Lower Natural Barrier comprises two features: the unsaturated zone below the repository and the saturated zone, both of which prevent or reduce the rate of radionuclide movement from the repository to the accessible environment through such processes as the slow movement of water and sorption of radionuclides onto mineral surfaces.

**Lower Natural Barrier: Unsaturated Zone Below the Repository**

The unsaturated zone below the repository provides a barrier capability to prevent or substantially reduce the rate of movement radionuclides.

> *"DOE explained in SAR Section 2.1.2.3.1 that downward flow from the repository occurs primarily in well-connected fracture networks in the Topopah Spring welded tuff. DOE explained in SAR Section 2.1.2.3.6 that radionuclides leaving the emplacement drift invert will enter either the repository host rock matrix (primarily under nondripping conditions, where advective flows through the invert are negligible) or the fractures (primarily under dripping conditions, where advective flows through the invert are relatively high). In DOE's unsaturated zone transport abstraction (SAR Section 2.3.8), radionuclides may be retarded by sorption in the matrix but not in fractures. However, radionuclides can migrate from fractures to the rock matrix by matrix diffusion. DOE identified matrix diffusion, coupled with sorption in the matrix, as contributing to barrier performance in the fracture-dominated flow paths. DOE explained in SAR Sections 2.1.2.3.1 and 2.1.2.3.6 that radionuclide travel times through the lower unsaturated zone are fast in the northern part of the repository area because fracture-dominated flow from the repository host rock encounters a low-permeability, sparsely fractured rock unit, the zeolitic Calico Hills nonwelded tuff, and the flow is diverted laterally along the interface into transmissive faults that connect with the water table. In contrast, DOE stated that in the southern part of the repository area, the fracture-dominated flow from the repository host rock passes into the vitric Calico Hills nonwelded tuff, a permeable rock unit that is dominated by matrix flow conditions. DOE also stated that low flow velocities and the opportunity for sorption in the rock matrix result in long transport times through the unsaturated zone in the southern part of the repository area, particularly for radionuclides that can undergo sorption in the matrix.*
>
> *DOE provided quantitative information on the barrier capability of the unsaturated zone below the repository in SAR Sections 2.1.2.3.6 and 2.3.8.5.4 and in DOE (2009an, Enclosures 1, 6, and 7). Using results from the TSPA model with median parameter values, SAR Figures 2.3.8-43 through 2.3.8-49 indicate that the barrier performance of the lower unsaturated zone varies according to the location of the radionuclide release (i.e., northern or southern part of the repository area) and the mode of release from the repository drift into the unsaturated zone (i.e., into fractures or matrix). DOE explained in SAR Sections 2.1.2.3.6 and 2.3.8.5.4 and in DOE (2009an, Enclosures 1, 6, and 7) that fracture flow dominates in the welded tuffs beneath the northern part and matrix flow dominates in the vitric Calico Hills tuff beneath the southern part of the repository. DOE stated that radionuclides released from a northern location will therefore tend to reach the water table much faster than those released from a southern location. However, initial releases into the*

*rock matrix will result in slow travel times regardless of release location. For example, DOE calculated that the median travel time of an unretarded tracer (Tc-99) through the lower unsaturated zone in the northern area is about 20 years for releases into fractures and about 5,000 years for releases into the matrix. For a southern release location, the calculated median travel times to the water table are slow regardless of whether releases are into fractures or the matrix, with either release mode resulting in a median arrival time of about 2,000 years (SAR Figure 2.3.8-49). Analyses documented in DOE (2009an, Enclosures 1, 6, and 7) showed that radioactive decay in the unsaturated zone coupled with a combination of matrix diffusion and sorption in the northern repository area and sorption in the vitric Calico Hills tuff layer in the southern repository area would substantially reduce releases of sorbing, short-lived radionuclides such as Cs-137. For longer lived radionuclides, DOE's analyses demonstrated that sorption slows but does not prevent their transport through the unsaturated zone. For example, DOE (2009an, Enclosure 7, Tables 1-5 through 1-8) indicated that the unsaturated zone beneath the repository (northern and southern areas combined) reduced the release of long-lived radionuclides such as Np-237 (weakly sorbing) and Pu-242 (moderately to strongly sorbing) from the engineered barrier system to the saturated zone by about 30–50 percent during the 10,000-year period and by about 5 to 30 percent over a million-year time frame."* (SER Vol. 3, pages 1-20 and 21)

## Lower Natural Barrier: Saturated Zone

The saturated zone provides a barrier capability to prevent or substantially reduce the movement of radionuclides.

*"In SAR Section 2.1.2.3.2, DOE explained that water in the saturated zone component of the lower natural barrier flows initially through approximately 12–14 km [7.4–8.7 mi] of fractured volcanic rocks. Beyond this distance, flow is predominantly within a saturated layer of alluvium. DOE explained that the flow in the fractured volcanic aquifers occurs primarily in the fractures. DOE explained that hydraulic conductivities are much lower in the matrix of the volcanic tuffs than in the fractures, because the rock matrix is more porous than the fractures. These relative properties support exchange of radionuclides between the fractures and matrix through matrix diffusion. Hence, diffusion into the matrix followed by matrix sorption function to delay radionuclide transport to the accessible environment. DOE explained that flow and transport occur in the intergranular pores of the alluvial sediments after leaving the fractured volcanic aquifer. Because of the low water velocity, the rate of radionuclide movement is slow, allowing more time for sorption to occur onto the mineral surfaces to further delay radionuclide transport to the accessible environment. DOE explained that the presence of colloids also affects the rate of movement of radionuclides in the saturated zone. Radionuclides embedded in or irreversibly sorbed onto colloids are retarded when the associated colloids are temporarily filtered from transport. Radionuclides that are sorbed reversibly to colloids are delayed by matrix diffusion in the volcanic aquifers and by sorption in the alluvial sediments.*

*DOE provided quantitative information on the barrier capability of the saturated zone in SAR Sections 2.1.2.3.6 and 2.3.9.3.4.1. SAR Figures 2.3.9-16 and 2.3.9-45 through 2.3.9-47 illustrated the combined effects of matrix diffusion and sorption in delaying radionuclide transport to the accessible environment. Median transport times ranged from about 10 to*

*10,000 years for nonsorbing radionuclides (e.g., Tc-99) and from 100 to 100,000 years for moderately sorbing radionuclides (e.g., Np-237). Median transport times generally exceeded 10,000 years for highly sorbing radionuclides (e.g., Pu-239). The median transport times for radionuclides irreversibly attached onto colloids ranged from 100 to 600,000 years. In DOE (2009an, Enclosures 6 and 7), DOE used TSPA model results to provide quantitative information on the barrier capability of the saturated zone in terms of reduction of radionuclide activity between the release from the unsaturated zone into the water table and the release into the accessible environment. DOE presented information on the performance of the saturated zone in DOE (2009an, Enclosure 7, Tables 1-5 through 1-8). This information indicates that DOE expects activities of soluble, short half-life radionuclides (e.g., Cs-137 and Sr-90) to drop by 100 percent during transport to the accessible environment. For radionuclides with moderate to strong sorption and long half-life (e.g., Np-237 and Pu-242), DOE calculated the activities to drop by 70 to 98 percent during the 10,000-year period and by 20 to 50 percent during the post-10,000-year period over the transport time in the saturated zone to the accessible environment."* (SER Vol. 3, pages 1-23 and 24)

## 1.2 Multiple Barrier Review

SER Section 2.2.1.1 "System Description and Demonstration of Multiple Barriers" describes the staff's review of each barrier's capability.

*"To evaluate the description of the barrier capability, the NRC staff reviewed how DOE*

- *Identified the safety classification and primary function of each barrier component*
- *Identified the characteristics and processes important to barrier capability, including both those that are potentially beneficial and those that are potentially detrimental to barrier functions*
- *Described how the barrier component was represented in the performance assessment*
- *Described the qualitative and quantitative capabilities of each barrier component, consistent with the performance assessment analyses*
- *Characterized the time period over which the barrier functions and how DOE expects the barrier capability to change over time*
- *Accounted for the uncertainty in the description of the barrier capability*

*To evaluate the technical bases for the barrier capability, the NRC staff reviewed the consistency between the descriptions of the barrier capability documented in SAR Section 2.1.2 and the technical bases summarized in SAR Section 2.1.3 and further documented in SAR Section 2.3. In addition, the NRC staff reviewed the description of the performance confirmation plan to determine whether it was consistent with the descriptions of barrier capability. SER Section 2.4 contains the results of the NRC staff's review of the performance confirmation plan.*

*The NRC staff also considered the insights gained from NRC (2005aa, Appendix D), as updated (CNWRA and NRC, 2008aa), to determine whether DOE had omitted any features or processes that might contribute significantly to barrier capability in its description of*

> *barrier capability. In addition, the NRC staff reviewed DOE's TSPA model described in SNL (2008ag) to assess consistency between the descriptions of barrier capability and how the TSPA model components actually represented the barrier capability."* (SER Vol. 3, pages 1-5 to 6)

Based on its review, the NRC staff found, with reasonable expectation, that the requirements at 10 CFR 63.115(a–c) were satisfied. As explained in the SER:

> *"The design features of the engineered barrier system and the natural features of the geologic setting that are considered barriers important to waste isolation have been identified. A description has been provided of the capability of barriers identified as important to waste isolation, and the NRC staff concludes that the description is consistent with the definition of a barrier at 10 CFR 63.2 because it describes a capability to prevent or substantially reduce the rate of water or radionuclide movement. The NRC staff further concludes that the description takes into account uncertainties in characterizing and modeling the barriers, and the technical basis for this description has been provided that is based on and consistent with the technical basis for the performance assessment."*
> (SER Vol. 3, pages 1-27 and 28)

## 1.3 Multiple Barrier Perspectives

Some stakeholders were concerned when NRC prescribed a different regulatory approach in Part 63 for multiple barriers (i.e. DOE has flexibility in identifying the multiple barriers and is required to support the basis for each barriers capability consistent with the performance assessment used to demonstrate compliance with the individual dose limit) than the multiple barrier approach in NRC's generic regulations in Part 60 for sites other than Yucca Mountain (e.g., specific quantitative subsystem requirements, such as a 300-1,000 year waste package lifetime). Appendix A provides a more comprehensive discussion of the basis for NRC adopting a different approach for multiple barriers in Part 63.

DOE identified the various components and features of its multiple barriers and explained how such features worked in combination to limit the releases of radionuclides to the compliance point (e.g., upper natural barrier limits the water that can contact waste packages, the engineered barrier system provides containment of the majority of the high-level waste within the waste package thorough out the entire compliance period, and for those radionuclides that exit the waste package, the lower natural barrier reduces the transport of those radionuclides to the accessible environment where there is the potential for human contact). Additionally, the staff's understanding of DOE's multiple barrier approach was used to risk inform its review to ensure those barrier features and components most important to safety were appropriately supported in the models and parameters used in the performance assessment.

It is important to note that the EBS provides a capability to retain the majority of the inventory in the waste package because the corrosion resistant material remains substantially intact and therefore allows limited water into the package and limited release of radionuclides from inside the package. In particular, (1) releases from most of the waste packages will be from diffusional release through stress corrosion cracks; and (2) general corrosion of the waste packages.

General corrosion that would allow water to enter the package and advective releases out of a waste package is of very limited occurrence - DOE predicted that the earliest general corrosion waste package failure (at the 95th percentile general corrosion rate) would occur at 560,000 years, and at 1 million years. About 10 percent of the waste packages are predicted to fail from general corrosion. Such significant performance from the EBS may indicate that the repository does not have multiple barriers. It is true that no releases can occur until the waste package is breached, however, that does not diminish the capabilities of the unsaturated and saturated zones for contributing to the effectiveness of the natural barriers. For example, as explained in the SER,

<u>Lower Natural Barrier (unsaturated zone)</u>

> *"For sorbing radionuclides, travel times depend on the radionuclide-specific sorption coefficient. More strongly sorbing aqueous species, such as Pu-242, have transport times on the order of hundreds of thousands of years and longer in the southern area. Some radionuclides that are dominant contributors to the total inventory are significantly delayed before reaching the water table due to sorption of radionuclides onto the rock matrix that exists in the southern area (e.g., Cs-137, Sr-90, Pu-239, Pu-240, Am-241, Am-243) [SAR Section 2.3.8]."* (SER Vol. 3, page 17-16)

<u>Lower Natural Barrier (saturated zone)</u>

> *"Flow in the alluvial portion of the flow system is conceptualized as relatively slow because the effective flow porosity is relatively high [average estimated value of 0.18 (SAR p. 2.3.9-59)]. Overall, the transport time for nonsorbing radionuclides ranges from about 10 years to several thousand years (SAR p. 2.3.9-9). Sorbing radionuclides can be significantly delayed by sorption to alluvium mineral grains in which case transport times for strongly sorbing radionuclides generally exceed 10,000 years (SAR p. 2.3.9-9). Table 17-5 provides transport times for select radionuclides representing a range of sorption behavior."*
> (SER Vol. 3, page 17-17)

Thus, the results of the performance assessment demonstrate, that non-sorbing radionuclides that are more mobile show up in the initial 10,000 years, whereas, the sorbing radionuclides are more significant during the analysis period after 10,000 years, which extends to 1 million years. However, releases are always within the regulatory dose limits as described in the SER:

> *"The average annual doses are largest for the seismic ground motion and igneous intrusive modeling cases (generally a factor of 10 or more larger than the other modeling cases; see SAR Figure 2.4-18). Tc-99 (a nonsorbing radionuclide) is the largest contributor to the average annual dose in the initial 10,000 years. Tc-99 accounts for approximately 0.001 mSv/yr [0.1 mrem/yr] of the peak of the overall average annual dose of approximately 0.003 mSv/yr [0.3 mrem/yr] (SAR Figure 2.4-20a). After 10,000 years and up to 1 million years, the peak of the overall average annual dose occurs at 1 million years, with Pu-242 and Np-237 being the largest contributors to the peak of the overall average annual dose. Pu-242 and Np-237 account for approximately 0.01 mSv/yr [1.0 mrem/yr] of the peak of the overall average annual dose of approximately 0.02 mSv/yr [2.0 mrem/yr] at 1 million years (SAR Figure 2.4-20b)."* (SER Vol. 3, page 17-18)

Thus, doses are well within the average annual individual dose limits of 15 mrem (in the initial 10,000 years) and 100 mrem (for the period after 10,000 years up to 1-million years) due to the multiple barriers working in combination to limit releases to the accessible environment.

## 1.4 References Specific to Multiple Barriers

CNWRA and NRC. 2008aa. “Risk Insights Derived From Analyses of Model Updates in the Total-system Performance Assessment Version 5.1 Code.” ML082240343. San Antonio, Texas: CNWRA.

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SNL. 2008ag. “Total System Performance Assessment Model/Analysis for the License Application.” MDL–WIS–PA–000005. Rev. 00. AD 01, ERD 01, ERD 02, ERD 03, ERD 04. ML090790353. Las Vegas, Nevada: Sandia National Laboratories.

# 2.0 Scenario Analysis

*"A performance assessment is a systematic analysis that answers the following risk triplet questions: What can happen? How likely is it to happen? What are the resulting consequences? Scenario analysis answers the first question: What can happen? A scenario is a well-defined, connected sequence of features, events, and processes (FEPs) that can be interpreted as an outline of a possible future condition of the repository system. Therefore, a scenario analysis identifies possible ways in which a geologic repository environment can evolve so that a defensible representation of the system can be developed to estimate consequences. The goal of scenario analysis is to ensure that no important aspect of the potential high-level waste repository is overlooked in the evaluation of its safety.*

*A scenario analysis is generally composed of four parts (Nuclear Energy Agency, 2001aa). First, a scenario analysis identifies FEPs relevant to the geologic repository system. Second, in a process known as screening, the scenario analysis evaluates and identifies FEPs for exclusion from or inclusion into the performance assessment calculations. Third, included FEPs are considered to form scenarios and scenario classes (i.e., related scenarios) from a reduced set of events. Fourth, the scenario classes are screened for implementation into the performance assessment."* (SER Vol. 3, page 2-1)

## 2.1 Requirements Specific to Scenario Analysis

Features, events, and processes (FEPs) are used to represent the scenarios that are evaluated in the performance assessment. NRC's regulations at Part 63 have specific requirements for inclusion of the FEPs (i.e., those that have a significant effect on performance) and for exclusion of FEPs based on the likelihood (i.e., the probability cut-off is 1 in 100,000,000 for demonstrating compliance with the individual protection standard and the cut-off is 1 in 100,000 for demonstrating compliance with the separate standards for groundwater protection and the human intrusion standard). Additionally, the Part 63 places certain requirements on the FEPs to be included for the period after 10,000 years. In particular:

*"The postclosure performance objectives of 10 CFR 63.113 stipulate that a performance assessment must be used to demonstrate compliance with (i) the individual protection standard after permanent closure (10 CFR 63.311); (ii) the human intrusion standard (10 CFR 63.321 and 63.322); and (iii) the separate standards for protection of groundwater (10 CFR 63.331). Requirements for any performance assessment used to demonstrate compliance with 10 CFR 63.113 for 10,000 years after disposal are presented in 10 CFR 63.114(a). Section 63.114(a)(4) requires that the performance assessment consider only FEPs consistent with the limits on performance assessment specified at 10 CFR 63.342. Section 63.114(a)(5)–(6) requires the applicant to provide the technical basis for either inclusion or exclusion of FEPs and also defines criteria for inclusion of the FEPs into the performance assessment [specific FEPs must be evaluated in detail if the magnitude and time of the resulting radiological exposures to the reasonably maximally exposed individual, or radionuclide releases to the accessible environment, for 10,000 years after disposal, would be significantly changed by their omission].*

*Section 63.113 also requires that the performance assessments used to demonstrate compliance with the individual protection standard after permanent closure, the human intrusion standard, and the separate standards for protection of groundwater must also meet the requirements of 10 CFR 63.342. The limits on performance assessments are defined in 10 CFR 63.342. According to 10 CFR 63.342(a), the performance assessment for 10,000 years after disposal to show compliance with 10 CFR 63.311(a)(1), 63.321(b)(1), and 63.331 shall not include FEPs with less than 1 chance in 100,000,000 per year of occurring. Also, 10 CFR 63.342(a) provides that the performance assessments need not evaluate the impacts resulting from any FEP or sequence of events and processes with a higher chance of occurring if the results of the performance assessments would not be changed significantly in the initial 10,000-year period after disposal.*

*An additional basis for excluding FEPs in the performance assessments used to demonstrate compliance with 10 CFR 63.321(b)(1) and 63.331 during the first 10,000 years after disposal is provided in 10 CFR 63.342(b). For those performance assessments, 10 CFR 63.342(b) states that unlikely FEPs or sequences of events and processes (i.e., those that are estimated to have less than 1 chance in 100,000 per year of occurring and at least 1 chance in 100 million per year of occurring) can be excluded from the performance assessment.*

*Section 63.342(c) specifies how to project the continued effects of FEPs beyond 10,000 years in the performance assessment models to show compliance with 10 CFR 63.311(a)(2) and 63.321(b)(2). Section 63.342(c) requires that DOE's performance assessment shall project the continued effects of the features, events, and processes included in 10 CFR 63.342(a) beyond the 10,000-year post disposal period through the period of geologic stability. Section 63.342(c)(1) requires that DOE assess the effects of seismic and igneous activity scenarios, subject to the probability limits in 10 CFR 63.342(a) for very unlikely features, events, and processes, or sequences of events and processes. Section 63.342(c)(1)(i) states that the seismic analysis may be limited to the effects caused by damage to the drifts in the repository, failure of the waste packages, and changes in the elevation of the water table under Yucca Mountain (i.e., the magnitude of the water table rise under Yucca Mountain). Section 63.342(c)(1)(ii) specifies limitations for the igneous activity analysis and igneous event. Section 63.342(c)(2) requires that DOE assess the effects of climate change; it also specifies that the climate change analysis may be limited to the effects of increased water flow through the repository as a result of climate change, and the resulting transport and release of radionuclides to the accessible environment. In addition, 10 CFR 63.342(c)(2) specifies that the nature and degree of climate change may be represented by constant-in-time climate conditions. Section 63.342(c)(3) requires that DOE assess the effects of general corrosion on engineered barriers and specifies that DOE may use a constant representative corrosion rate throughout the period of geologic stability or a distribution of corrosion rates correlated to other repository parameters."* (SER Vol. 3 pages 2-2 and 2-3)

## 2.2 Performance Perspectives on Scenario Analysis

*"The NRC staff evaluated the technical bases of the 222 excluded FEPs. In reviewing the technical bases for exclusion of FEPs, the NRC staff focused in greater detail on items that were deemed to have the largest impact on risk and used progressively less detail on items that were considered to have lower to negligible impact on risk. For example, drift collapse is a process that could affect multiple aspects of the repository (e.g., temperature, moisture*

*distribution, rock loads acting on the drip shield, response of the drip shield subjected to seismic excitations; Ofoegbu, et al., 2007aa) and that could affect the performance of multiple engineered barrier components which impact risk (NRC, 2005aa). Accordingly, the NRC staff devoted greater effort to evaluate the technical basis for exclusion of the Drift Collapse FEP. On the other hand, a number of FEPs were deemed to be not risk significant (e.g., Meteorite Impact, Copper Corrosion in the Engineered Barrier System), and these FEPs were reviewed in less detail."* (SER Vol. 3 page 2-4)

## 2.3 Key Review Topics for Scenario Analysis

The screening of features, events, and processes (FEPs) begins with a complete list of FEPS that is then examined for either inclusion into or exclusion from the assessment.

**1) Identification of a List of FEPs**

- Based on an iterative approach, including expanding on the initial FEPs list, brainstorming, multiple reviews by subject matter experts, top-down elicitation from an independent classification scheme, and use of the Yucca Mountain project analyses DOE's count of all FEPs was 374 (SNL 2008ac, p. 6-4) – SER Vol. 3 page 2-5

- DOE compared its FEPs list to a version of the international list of FEPs by the Nuclear Energy Agency, Organisation for Economic Co-operation and Development (OECD) (Nuclear Energy Agency, 2000aa, Appendix D) to evaluate the completeness of the list of FEPs; additionally, DOE noted that the International FEPs Database was updated in 2006 (Nuclear Energy Agency, 2006aa) and concluded the update did not present additional information beyond the FEPs already addressed in the FEPs list for the license application (SAR page 2.2-8 and in SNL [2008ab, Appendix F]) – SER Vol. 3 page 2-5

- DOE's FEPs list (SAR Table 2.2-5) included FEPs which address potentially disruptive events related to igneous activity (e.g., FEP 1.2.04.03.0A and FEP 1.2.04.07.0A); seismic shaking (e.g., FEP 1.2.03.02.0A and FEP 1.2.03.02.0B); tectonic evolution (e.g., FEP 1.2.01.01.0A); climatic change (e.g., FEP 1.3.01.00.0A and FEP 1.3.07.02.0B); and criticality (e.g., FEP 2.1.14.16.0A and FEP 2.1.14.17.0A) – SER Vol. 3 page 2-6

- DOE identified design control parameters that describe the bases of the repository design (SAR Table 1.9-9) that provided a basis for exclusion of certain FEPs based on the use of relevant materials – SER Vol. 3 page 2-11)

**2) Screening of FEPS, Including Assessment of Final Part 63 for 1-million years**

- DOE identified (in DOE 2009cb, Enclosure 1) that it considered the probability criterion to screen all types of FEPs, rather than selectively applying the probability criterion to events only (i.e., the probability criterion was also considered for features and processes) – SER Vol. 3 page 2-7

- DOE submitted its application prior to the finalization of Part 63, therefore, DOE (2009cb, Enclosure 6) performed a detailed comparison between the proposed 10 CFR Part 63 (NRC, 2005af) rule and the final 10 CFR Part 63 rule that became effective on April 13, 2009, and identified material changes in the final rule and how those changes may impact the license application; Enclosure 6 specifically discussed (i) the post-10,000-year 10 CFR Part 63 individual protection standard (350 mrem vs. 100 mrem); (ii) arithmetic mean of projected doses; (iii) water table rise due to seismic activity [an additional requirement added to 10 CFR 63.342(c)(1)(i) in the final rule]; (iv) changes to the range of deep percolation rates; and (v) dosimetry – (SER Vol. 3 page 2-7)

- FEPs related to water chemistry were reviewed by following multidisciplinary teams of NRC staff for: Quantity and Chemistry of Water Contacting Engineered Barriers and Waste Forms, Degradation of Engineered Barriers, and Radionuclide Release and Solubility Limits (Leslie, 2010aa) – SER Vol. 3 pages 2-9 and 2-10

**3) Screening of Erosion/Denudation (FEP 1.2.02.01.0A)**

- DOE stated that the maximum expected erosion of 6 cm [2.4 in] in 10,000 years is consistent with existing surface irregularities and that erosion would be negligible compared with the minimum distance of 200 m [656.2 ft] from the ground surface to the repository emplacement areas (SNL, 2008ab) – SER Vol. 3 page 2-16

- Erosion rates DOE cited are consistent with the site description data at BSC (2004bi) – SER Vol. 3 page 2-17

**4) Screening of Human Influences on Climate (FEP 1.4.01.00.0A)**

- DOE excluded Human Influences on Climate on the basis that proposed 10 CFR 63.305 excludes speculative prediction of changes to human behavior (SNL 2008ab) – SER Vol. 3 page 2-20

**5) Screening of Hydrologic Response to Seismic Activity (FEP 1.2.10.01.0A)**

- DOE excluded Hydrologic Response to Seismic Activity on the basis of low consequence (SNL, 2008ab) and the technical basis for the exclusion of this FEP was supplemented as described in DOE (2009ab Enclosure 19; 2009by Enclosures 1–6; 2009bz Enclosure 1; 2009ca Enclosures 1–2; 2009cb Enclosure 6) – SER Vol. 3 page 2-17

- SNL (2008ab) presented modeling investigations that have been conducted to estimate the hydrologic response (i.e., change in water table elevations), given predicted fault displacements (National Research Council, 1992aa, Chapter 5) – SER Vol. 3 page 2-17

**6) Screening of Recycling of Accumulated Radionuclides from Soils to Groundwater (FEP 1.4.07.03.0A)**

- DOE excluded Recycling of Accumulated Radionuclides from Soils to Groundwater on the basis of low consequence using a recycling model that estimated effects on the total system performance results stating recycling could increase the total mean annual dose by approximately 7 to 11 percent for the seismic ground motion and igneous intrusion scenarios for the 1-million-year simulation period and by an average of 11 percent for the 10,000-year simulation period, which is not significant compared with the range of uncertainty simulated by the total system performance assessment model (SNL, 2008ab and DOE 2009af Enclosures 3 and 4) - SER Vol. 3 pages 2-22 and 2-23

**7) Screening of Drift Collapse (FEP 2.1.07.02.0A)**

- DOE stated that drift degradation could occur rapidly if the stress change is large enough to cause instantaneous rock failure or gradually if the stress change is too small to cause rapid failure but large enough to weaken the rock with time; DOE summarized its basis for excluding drift collapse in SNL (2008ab) – SER Vol. 3 page 2-32

- Mechanical behavior of drifts for five rock-strength categories of lithophysal rock was analyzed by DOE (BSC 2004al, Section 6.4.2.1) using the UDEC computer code that is used internationally by the rock mechanics and mining industries both as a research tool and a design tool - SER Vol. 3 page 2-32

- NRC staff performed independent calculations using analytical tools and numerical models to assess potential issues and to verify or confirm the applicant's conclusions (Cao, 2010aa) – SER Vol. 3 page 2.32

- DOE also supplemented its technical basis, in responses to NRC staff's request for additional information, in DOE (2009ae Enclosures 1–8; 2009cd, Enclosure 1; 2009ce Enclosure 1–2; 2009cf Enclosure 1; 2009cg Enclosure 1; 2009ch Enclosure 1) – SER Vol. 3 page 2-33

- DOE (2009ce, Enclosure 1) provided additional details on the stress-strain relationships for lithophysal rocks, which showed that the tested rocks have a more ductile response (i.e., less prone to failure at peak stress) than the simulated rock mass in the UDEC (Itasca International, Inc., 2004ac), as described in BSC (2004al) models – SER Vol. 3 page 2-35

- NRC staff's confirmatory calculations (Cao, 2010aa) showed that an overstressed zone is expected to occur within the first tens of centimeters of the drift wall, which is comparable to the depths calculated in DOE (2009cd, Enclosure 1) – SER Vol. 3 pages 2-39 and 2-41

**8) Screening of Localized Corrosion on Waste Package Outer Surface due to Deliquescence (FEP 2.1.09.28.0A)**

- DOE excluded Localized Corrosion on Waste Package Outer Surface Due to Deliquescence on the basis of low consequence (SNL, 2008ab) and supplemented its technical basis for exclusion in DOE (DOE, 2009ab, Enclosures 12–15). – SER Vol. 3 page 2-53

- DOE provided preliminary experimental results to support its basis that there is no evidence localized corrosion could initiate and be sustained for extended periods in deliquescent solutions (BSC [2005aa, Section 6.4.2.2(a)] and DOE 2009ab Enclosures 12–15) – SER Vol. 3 pages 2-53 and 2-54

**9) Screening of Criticality (FEPs 2.1.14.15.0A through 2.1.14.26.0A and 2.2.14.09.0A through 2.2.14.12.0A)**

- SAR Section 2.2.1.1.2 states the potential for criticality events is determined by a number of precursor conditions that must occur for the inventory to achieve a potentially critical configuration; an initiating event must occur which causes a breach of the waste package before any other sequence of events on that waste package could lead to criticality after which additional precursor conditions include (i) presence of a moderator (i.e., water), (ii) separation of fissionable material from the neutron absorber material or an absorber material selection error during the canister fabrication process, and (iii) the accumulation (external) or presence of a critical mass of fissionable material in a critical geometric configuration; as described by the applicant in SNL (2008ab), the probability of developing a configuration with criticality potential is insignificant unless the initiating event and all three of the precursor conditions are realized - SER Vol. 3 page 2-65

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# 3.0 Events with Probabilities Greater Than $10^{-8}$ Per Year

*A performance assessment evaluation that is used to demonstrate compliance with the individual protection standard for the proposed Yucca Mountain repository must consider events that have at least 1 chance in 100 million per year of occurring. To address this requirement, DOE identified and described those events that exceeded this probability threshold ($10^{-8}$ per year). Performance assessments are also used to demonstrate compliance with the human intrusion and groundwater protection standards. These performance assessments have different considerations for event probabilities than those required for the individual protection standard and are evaluated in SER Sections 2.2.1.4.2 and 2.2.1.4.3, respectively.* (SER Vol. 3 page 3-1)

## 3.1 Requirements Specific to Events with Probabilities Greater Than $10^{-8}$ per year

Scenarios included in the performance assessment are to be weighted by the associated for the probability scenario. NRC's regulations at Part 63 have specific requirements for inclusion of the FEPs that have a significant effect on performance and for exclusion of FEPs based on the likelihood (i.e., the probability cut-off is 1 in 100,000,000 for demonstrating compliance with the individual protection standard and the cut-off is 1 in 100,000 for demonstrating compliance with the separate standards for groundwater protection and the human intrusion standard). Thus, each scenario has an associated probability to weight the consequence estimate in the performance assessment. The regulations define the performance assessment to be an analysis that:

*"(1) Identifies the features, events, processes (except human intrusion), and sequences of events and processes (except human intrusion) that might affect the Yucca Mountain disposal system and their probabilities of occurring during 10,000 years after disposal;*

*(2) Examines the effects of those features, events, processes, and sequences of events and processes upon the performance of the Yucca Mountain disposal system; and*

*(3) Estimates the dose incurred by the reasonably maximally exposed individual, including the associated uncertainties, as a result of releases caused by all significant features, events, processes, and sequences of events and processes, weighted by their probability of occurrence."* (10 CFR 63.2)

## 3.2 Performance Perspectives on Events with Probabilities Greater Than $10^{-8}$ per year

DOE retained igneous activity, seismic activity, and early failure events in its performance assessment (i.e., the igneous scenario, the seismic scenario, and the early failure scenario respectively) to demonstrate compliance with the individual protection standard at 10 CFR 63.311.

## 3.3 Key Review Topics for Events with Probabilities Greater Than $10^{-8}$ per year

The assignment of probabilities for igneous activity, seismic activity, and early failure events is an important aspect of the NRC's review, in part, because the consequences are weighted by the probability in estimating the results of the performance assessment.

**1) Igneous Event Probabilities**

- DOE characterized the basaltic volcanism in the Crater Flat volcanic field, which is in close proximity to Yucca Mountain, as having a relatively long lifetime with a small volume of erupted material - the geochemical data indicates that the intensity of mantle melting processes beneath the Yucca Mountain region has waned over the past 5 million years(SAR Section 1.1.6.1.1) – SER Vol. 3 page 3-5

- DOE conducted an expert elicitation (Probabilistic Volcanic Hazard Assessment [PVHA] – CRWMS M&O 1996a) and an update – PVHA update (SNL 2008ah) – SER Vol. 3 page 3-5 [also Section 20 of this document has further details on review of the expert elicitation process]

- The probability of an eruptive conduit event developing within the repository differed between the PVHA and its update by a factor of 2.5 ($4.8 \times 10^{-9}$ versus $1.2 \times 10^{-8}$ per year, respectively); however, the two values are not directly comparable for the reason stated in (Boyle, 2008aa) – SER Vol. 3 page 3-7

- Doses DOE calculated for the intrusive and extrusive (volcanic) igneous cases (SAR Section 2.4) are on the order of 0.01 mSv/yr [1 mrem/yr] or less, two or more orders of magnitude below the dose limits. An approximate doubling of the igneous probabilities would have no significance to risk (SNL, 2008ah; Boyle, 2008aa) – SER Vol. 3 page 3-7

- DOE concluded that the annual chance of an igneous event recurrence within the repository lifetime is less than 1 in 10,000 during 10,000 years (SAR Sections 2.2.2.2.2.1 and 2.3.11.2.1.1; see also Detournay, et al., 2003aa) because there has been a sufficient time lapse since caldera-forming volcanic activity ended about 8 million years ago (BSC, 2004bi) – SER Vol. 3 page 3-8

- The NRC staff also conducted independent investigations in the Yucca Mountain region to support the evaluation of uncertainties in the location, age, and characteristics of buried igneous features (e.g., Magsino, et al., 1998aa; Stamatakos, et al., 1997ab; Hill and Connor, 2000aa; Hill and Stamatakos, 2002aa; Stamatakos, et al., 2007aa) – SER Vol. 3 page 3-9

**2) Seismic Event Probabilities**

- DOE conducted an expert elicitation on probabilistic seismic hazard assessment in the late 1990s (CRWMS M&O, 1998aa; BSC, 2004bp) – SER Vol. 3 page 3-12

- DOE conditioned the probabilistic seismic hazard assessment ground motion results to constrain the large low-probability ground motions to ground motion levels that, according to DOE, are more consistent with observed geologic and seismic conditions at Yucca Mountain, as provided in BSC (2005aj) – SER Vol. 3 page 3-12

- The probabilistic seismic hazard assessment was supported by a broad range of data, process models, empirical models, and seismological theory, which included (i) cause and effect analysis of recent instrumented events such as the 1992 MW 5.6 Little Skull Mountain earthquake (where MW is the moment magnitude); (ii) historic seismicity included in the probabilistic seismic hazard assessment historic catalog [as provided in CRWMS M&O (1998aa, Appendix G)]; (iii) ground motion parameters derived from empirical studies of worldwide ground motion data (e.g., Spudich, et al., 1999aa); and (iv) 52 exploratory trenches and excavations across fault traces with known or suspected Quaternary Period (last ~1.8 million years) fault movements (Keefer, et al., 2004aa) – SER Vol. 3 pages 3-13 and 3-14

- For the largest mapped faults at Yucca Mountain (i.e., those that form the boundary of the major fault block that comprises the Yucca Mountain geologic features), the probabilistic fault displacement hazard curves were largely based on the same detailed paleoseismic and earthquake data used to characterize these faults as potential seismic sources (CRWMS M&O, 1998aa) – SER Vol. 3 page 3-14

**3) Early Waste Package and Drip Shield Failures Probabilities**

- DOE obtained qualitative and quantitative information on the types of manufacturing defects and handling errors that may occur and their associated frequency of occurrence, as identified in SNL (2007aa, Section 6.1) – SER Vol. 3 page 3-20

- Given that the industrial analogues are only partly analogous to the waste package and drip shield in terms of manufacturing techniques, intended safety function, and operating environment, DOE determined that only some of the generic defects applicable to welded metallic containers are applicable to the waste package and drip shield (SAR Sections 2.3.6.6.3.1 and 2.3.6.8.4.3.1 and SNL 2007aa Section 6.1.6) – SER Vol. 3 page 3-20

- In DOE’s response to NRC staff’s request for additional information (DOE, 2009ac), DOE stated that the composition of the base metal for the waste package and drip shield will be certified by the supplier and independently checked upon receipt at the fabrication facility – SER Vol. 3 pages 3-24 and 3-26

## 3.4 References Specific to Events with Probabilities Greater Than $10^{-8}$ per year

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# 4.0 Degradation of Engineered Barriers

Engineered barriers are designed and constructed to prevent water from contacting the waste packages and waste forms while the total activity of the waste is still high and prevent the release of any radionuclides into the environment. Importantly, radionuclide decay reduces the overall hazard of the waste, and for certain short-lived radionuclides it can be expected that the inventory will decay away to a risk insignificant level while inside a waste package that has not been breached within several 100 of years (e.g., Cs-137 and Sr-90 with half-lives of approximately 30 and 29 years respectively). Other long-lived radionuclides (e.g., I-129 and Np-237 with half-lives of 16 million and 2 million years, respectively) will persist for such long time periods that the extent of damage to the waste package does affect the risk posed by their potential release. Thus, it is important for performance assessments to estimate both the timing and extent of the damage to engineered barriers that degrade under processes such as general corrosion, pitting corrosion, and stress corrosion cracking.

> *"Safety Evaluation Report (SER) Section 2.2.1.3.1 addresses the chemical degradation of the drip shield and waste packages stored in the repository drifts. The drip shield and the waste packages are engineered barriers, a subset of the Engineered Barrier System. The general functions of the Engineered Barrier System are to (i) prevent or significantly reduce the amount of water that contacts the waste, (ii) prevent or significantly reduce the rate at which radionuclides are released from the waste, and (iii) prevent or significantly reduce the rate at which radionuclides are released from the engineered barrier system to the Lower Natural Barrier"* (SER Vol. 3, page 4-1)

## 4.1 Requirements Specific to Degradation of Engineered Barriers

The regulations at 10 CFR 63.342(c)(3) specify that the performance assessment for the period beyond 10,000 years must assess the effects of general corrosion on engineered barriers and that DOE may use a constant representative corrosion rate throughout the period of geological stability or a distribution of corrosion rates correlated to other repository parameters.

> "For the period beyond 10,000 years following permanent closure, the applicant has chosen to assess the effects of general corrosion on engineered barriers in its performance assessment by using a distribution of corrosion rates correlated to other repository parameters [10 CFR 63.342(c)(3)]." (SER Vol. 3, page 4-2)

## 4.2 Perspectives on Performance of Engineered Barriers

The drip shield provides protection from seepage water dripping onto the waste package that is important for limiting the potential for localized corrosion of the waste package (the initial 12,000 years when waste packages are sufficiently hot that specific chemical and thermal conditions may support localized corrosion on the surface of the waste package). DOE provided information supporting drip shield lifetimes much longer than 12,000 years:

> *"Most plate failures occur between 100,000 and 300,000 years after repository closure. DOE stated that there is negligible probability of drip shield breach within 12,000 years after repository closure because the general corrosion rate of the Titanium Grade 7 drip shield*

*plates is low, and the likelihood of plate failure by a seismic event is negligible before that time period. For the Titanium Grade 29 structural supports, DOE calculated that most drip shield frameworks failed between 20,000 and 170,000 years after repository closure, using the model described in SAR Section 2.3.6.8.1 and DOE (2009cn, Enclosure 2, Figure 1). For the alternative approach, in which DOE assumed equivalent corrosion rates for the structural supports and the plate, DOE calculated that most frameworks failed between about 80,000 and 170,000 years after repository closure, as shown in DOE (2009cn, Enclosure 2, Figure 1)."* (SER Vol. 3, Page 4-14)

Waste is not released from an intact waste package. Once a waste package is breached the amount of water that can enter the waste package and the release of radionuclides may still be limited depending on the extent of the damage (e.g., small cracks significantly limit potential releases whereas breaches of a larger area due to corrosion can allow more release). DOE provided information indicating the long-lifetime waste packages and the limited size of breaches:

*"A mean of less than 10 percent of CSNF waste packages are breached over 1 million years, and of the breached waste packages, the mean breached area is less than 0.3 percent of the total waste package surface area. The results for the codisposal waste package in the Nominal Modeling Case are similar (SAR Figure 2.1-17[b]). DOE (2009bj, Enclosure 1, Figures 9 and 10) showed the fraction of CSNF and codisposal waste packages, respectively, breached by general corrosion in the Seismic Ground Motion Modeling Case. For both waste packages, the mean is approximately 10 percent breached in 1 million years. DOE Enclosure 1, Figures 11 and 12 of its response to the NRC staff's request for additional information (DOE, 2009bj) showed the fraction of the surface area breached for the CSNF and the codisposal waste packages breached by general corrosion in the Seismic Ground Motion Modeling Case. For both waste packages, the fraction is approximately 1 percent of the surface area."* (SER Vol. 3 page 4-32)

## 4.3 Key Review topics for Degradation of Engineered Barriers

Review of the degradation of the engineered barriers considers both the role of drip shield (e.g., preventing water from contacting the waste package especially during the thermal period when the waste package is more sensitive to corrosion processes depending on the chemical conditions on the surface of the waste package) and the timing and extent of damage (e.g., pits, cracks, and general corrosion breaches) to the waste package.

*"DOE concluded that seepage flux is the primary source of water that may react with the engineered barrier system components (SAR Section 2.3.7.12.1). In DOE's model for flow of seepage water through the engineered barrier system, the water must first pass through the drip shield and then through the waste package before contacting and mobilizing the waste form. As such, SER Section 2.2.1.3.1 first concentrates on DOE's models for chemical degradation of the drip shield and then addresses DOE's models for chemical degradation of the waste package."* (SER Vol. 3, page 4-3)

The NRC staff considered DOE's technical basis as well as other information such as independent tests and analyses by NRC staff and its contractors in evaluating the license application. Key topics presented in the SER and key references are provided below for the degradation of the drip shield and waste package.

### 4.3.1 Drip Shield Degradation

The drip shield performs a key safety function of preventing seepage water from contacting the waste package during the time period when localized corrosion might occur (i.e., the initial 12,000 years after repository closure). DOE identified general corrosion and early failure of the drip shield due to manufacturing- and handling-induced defects as degradation mechanisms that were included in the performance assessment. (SER Vol. 3, page 4-4)

The passive film stability, while it persists, provide for the stability of titanium alloys over wide ranges of chemical potential and pH. The NRC noted that "uncertainty in the long-term persistence of the titanium passive film is primarily related to potential passive film degradation by fluoride-bearing brines" and concluded "that there is no evidence of localized corrosion of Titanium Grade 7 exposed to fluoride-bearing simulated concentrated water for 5 years and thus that the passive film is stable when in contact with a brine having this composition" (SER Vol. 3, page 4-6).

The NRC review considered the passive film stability, the general corrosion rate, and the early failure of the drip shield due to manufacturing defects.

**1) Drip Shield's Long-Term Passive Film Stability**

- Based on low consequence or low probability, DOE excluded all features, events, and processes (FEPs) related to chemical degradation of the drip shields with the exception of general corrosion and early failure of drip shields (SAR Table 2.2-5) - SER Vol. 3 pages 4-3 to 4-4

- DOE evaluated stability of passive films over a wide range of conditions, including possible degradation by fluoride-bearing seepage water brines (BSC 2004as Sections 1.1 and 6.5.7) – SER Vol. 3 page 4-5

- NRC independent tests of passive film degradation with fluoride concentration (Brossia et al., 2001aa) – SER Vol. 3 page 4-6

- NRC independent analysis of fluoride concentration in simulated concentrated water (Pabalan 2010aa) – SER Vol. 3 page 4-6

**2) General Corrosion of Drip Shield**

- DOE response to NRC request for addition information that corrosion rate is independent of temperature (DOE 2009cn, Enclosure 3) – SER Vol. 3 page 4-6

- NRC independent analysis corrosion rates do not show significant temperature dependence (Mintz and He 2009aa) – SER Vol. 3 page 4-7

- DOE corrosion rates based on data from weight-loss corrosion tests at the Long-Term Corrosion Test Facility (SAR Section 2.3.6.8.1.2.1) – SER Vol. 3 page 4-7

- DOE response to NRC request for addition information on experimental uncertainties (DOE 2009cn, Enclosure 5) – SER Vol. 3 page 4-9

- DOE response to NRC request for addition information with respect to the adequacy of immersion test conditions to determine corrosion rates (DOE 2009cn, Enclosure 4) – SER Vol. 3 page 4-9

- NRC independent confirmatory tests of corrosion rates under dripping conditions found rates that were less than those determined by immersion tests (He 2011aa and Jung, et al., 2011aa) – SER Vol. 3 page 4-10

**3) Drip Shield Early Failure**

- DOE report on low probability for drip shield early failure (SNL 2008ag) – SER Vol. 3 pages 4-15 and 4-16

### 4.3.2 Waste Package Degradation

An intact waste package prevents the release of radionuclides, thus the timing of a waste package breach and the extent of the breach (e.g., pits, cracks, and general corrosion breaches) are important for estimating potential releases. As with the drip shield, passive film stability, while it persists, is important for estimating chemical degradation of the waste package.

> *"In the TSPA analysis, DOE calculated that, due to its corrosion resistance, the waste package will significantly reduce the amount of water contacting the waste form for hundreds of thousands of years after repository closure (SAR Section 2.1.2.2.6). Because of the importance of the waste package in the postclosure performance assessment, the NRC staff reviewed DOE's model abstractions for waste package chemical degradation. In the context of these reviews, the NRC staff notes that DOE attributed the high corrosion resistance of Alloy 22, in part, to the presence of its passive film. In the event of deterioration or loss of waste package passivity, the time to waste package breach may be sooner and the size of the breached area may be larger than DOE calculated in the TSPA code. As such, DOE stated that long-term persistence of the passive film on Alloy 22 is one of the key issues that it considered to determine the long-term performance of the waste package in the repository, as described in SNL (2007al, Section 6.4.1.1). In NRC (2005aa, Appendix D, Section 4.3.1), the NRC also identified the long-term persistence of the passive film on the waste package outer barrier as being of high significance to risk for waste isolation."* (SER Vol. 3, page 4-17)

The NRC review considered the passive film stability for Alloy 22, the general corrosion rate for Alloy-22, stress corrosion cracking, and localized corrosion (e.g., pitting). In addition, the NRC considered the potential for the early failure of the Titanium Grade 7 drip shield due to manufacturing and handling induced defects.

**1) Passive Film Stability for Alloy 22 under Repository Conditions**

- DOE evaluated a wide range of FEPs related to chemical degradation of the waste package and included general corrosion, stress corrosion cracking, localized corrosion, microbially influenced corrosion, and early failure of drip shields in the performance assessment (SAR Table 2.2-5) - SER Vol. 3 pages 4-16 and 4-17

- DOE indicated stability of Alloy 22 passive film depends primarily on its physical and chemical properties (SNL 2007al) – SER Vol. 3 page 4-18

- DOE response to NRC request for addition information on the effect of carbon deposits (or organic deposits) on long-term passivity and corrosion behavior (DOE 2009cl and 2010ae) – SER Vol. 3 page 4-19

- Descriptions of the passive film for Alloy 22 and analogous nickel-based materials reported by NRC staff (Dunn, et al., 2005aa) and others (Lloyd, et al., 2003aa, 2004aa; Gray, et al., 2006aa; Montemor, et al., 2003aa; Hur and Park, 2006aa; Mintz and Devine, 2004aa) – SER Vol. 3 page 4-19

- DOE response to NRC request for addition information on the effect of anodic sulfur segregation on passive film stability (DOE 2009cl, Enclosure 5) – SER Vol. 3 page 4-20

- DOE response to NRC request for addition information on the effect of dripping conditions on passive film stability (DOE 2009cm, Enclosure 1) – SER Vol. 3 page 4-21

- NRC independent analysis of the impact of dripping waters on Alloy 22 corrosion (Dunn et al., 2006ab) – SER Vol. 3 page 4-22

- DOE response to NRC request for addition information on the effect of silica deposits on Alloy 22 passivity (DOE 2009cl, Enclosure 4 and DOE 2009cm, Enclosure 2) – SER Vol. 3 page 4-23

**2) General Corrosion of the Waste Package Outer Barrier (Alloy 22)**

- DOE's general corrosion rate is a function of the waste package temperature and at a given temperature is assumed constant over time (SAR Section 2.3.6.3.1) – SER Vol. 3 pages 4-23 and 4-24

- DOE corrosion tests in the Long-Term Corrosion Test Facility (SAR Section 2.3.6.3.2.1) – SER Vol. 3 page 4-25

- DOE response to NRC request for additional information regarding inadequate cleaning in weight-loss measurements (DOE 2009cl, Enclosure 3) – SER Vol. 3 pages 4-26 and 4-28

- DOE response to NRC request for additional information regarding effect of microbially influenced corrosion on general corrosion (DOE 2009cl, Enclosure 10) – SER Vol. 3 page 4-30

- NRC independent test showing decrease of corrosion rate with time (Dunn et al., 2005aa) – SER Vol. 3 page 4-30

- NRC independent tests for corrosion rates at elevated temperatures (Yang et al., 2007aa) – SER Vol. 3 page 4-30

**3) Localized Corrosion of the Waste Package Outer Barrier (Alloy 22)**

- DOE response to NRC request for additional information regarding in-drift conditions may support localized corrosion for ~12,000 years after closure (DOE 2009dg, Enclosure 1) – SER Vol. 3 pages 4-34 and 4-35

- DOE response to NRC request for additional information regarding effects of microbes on corrosion (DOE 2009cl, Enclosure 10) – SER Vol. 3 page 4-39

- NRC contractor independent test regarding sodium chloride solutions not initiating localized corrosion (He and Dunn 2005aa) – SER Vol. 3 page 4-38

**4) Stress Corrosion Cracking of the Waste Package Outer Barrier (Alloy 22)**

- DOE constant-load crack initiation tests (SAR Section 2.3.6.5.2.1.1), slow strain rate tests (SAR Section 2.3.6.5.2.1.2), and U-bend stress corrosion cracking initiation tests (SAR Section 2.3.6.5.2.1.3) – SER Vol. 3 page 4-44

- DOE response to NRC request for additional information regarding observed case of stress corrosion cracking initiation in simulated concentrated water (DOE 2009cj, Enclosure 1) – SER Vol. 3 page 4-45

- DOE response to NRC request for additional information regarding stress corrosion cracking induced by impacts during seismic ground motion (DOE 2009bj) – SER Vol. 3 page 4-54

- DOE report on the residual stress profile of welds (SNL 2007bb Section 6.5) – SER Vol. 3 page 4-49

- NRC independent tests on stress corrosion cracking susceptibility of Alloy 22 (Chiang et al., 2005aa, 2006aa) – SER Vol. 3 page 4-47

**5) Waste Package Early Failure due to Manufacturing- and Handling-Induced Defects**

- DOE information on the low probability for early failure (SNL 2008ag, Table 6.4-1) – SER Vol. 3 page 4-56

## 4.4 References Specific to Degradation of Engineered Barriers

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## 5.0 Mechanical Disruption of Engineered Barriers

Engineered barriers (e.g., drip shield and waste package) are subject to mechanical disruption due to such events as disruptive seismic events and the accumulation for rock rubble inside the repository drifts.

> *"Safety Evaluation Report (SER) Section 2.2.1.3.2 evaluates the performance of the proposed Engineered Barrier System (EBS) that the U.S. Department of Energy (DOE) presented in its Safety Analysis Report (SAR), Section 2.3.4 (DOE, 2008ab). The design aspects of the EBS were described in SAR Sections 1.3.4 and 1.5.2, while the performance aspects were described in SAR Sections 2.1, 2.3.4, 2.3.5, 2.3.6, and 2.3.7. DOE stated that the following EBS features contribute to barrier performance: emplacement drifts, drip shields, waste packages, waste forms, waste form internals, waste package pallets, and emplacement drift inverts. According to DOE, the EBS features are designed to work together with the natural barriers to prevent or substantially reduce the release rate of radionuclides from the repository to the accessible environment. A disruption of the EBS components has the potential to affect their barrier performance. DOE anticipates that mechanical disruption of EBS components could generally result from external loads generated by accumulating rock rubble. Rubble accumulation can result from processes such as (i) degrading emplacement drifts due to thermal loads, (ii) time-dependent natural weakening of rocks, and (iii) effects of seismic events (vibratory ground motion or fault displacements). SER Section 2.2.1.3.2 evaluates the performance of the various EBS components under a reasonable range of anticipated loading conditions."*
> (SER Vol. 3, page 5-1)

> *"The U.S. Nuclear Regulatory Commission (NRC) staff's review followed the guidance provided in the Yucca Mountain Review Plan (YMRP) (NRC, 2003aa), as supplemented by NRC (2009ab). YMRP Section 2.2.1 provides guidance to the NRC staff on applying risk information throughout the review of the performance assessment. The NRC staff used DOE's risk information that it derived from a review of DOE's treatment of multiple barriers, as appropriate. The NRC staff's review approach is to assess the DOE design and analyses of EBS components under anticipated demands generated by drift degradation due to seismic loads. For those cases in which the design capacities may be exceeded, the NRC staff examined the potential for continued functionality of the components under a range of anticipated conditions. On the basis of the risk insights developed, the NRC staff's review focuses primarily on the seepage barrier functionality of the drip shield and the potential for loads from accumulated rubble to be transferred onto the waste package. In considering the range of possible loads and temperature conditions that can be anticipated during the repository life, the NRC staff takes into account uncertainty and variability in (i) rock characterization data, (ii) laboratory and in-situ test results, (iii) modeling approaches and conceptualization of failure modes, and (iv) NRC staff's independent verifications."* (SER Vol. 3, page 5-2)

## 5.1 Requirements Specific to Mechanical Disruption of Engineered Barriers

Consideration of seismic activity is subject to specific requirements for the period after 10,000 years. First, 10 CFR 63.342(c)(1) specifies the effects of seismic and igneous activity scenarios are subject to the probability limits in 10 CFR 63.342(b) [i.e., performance assessments do not include those features, events, and processes that are estimated to have less than one chance in 100,000 of occurring]. Second, 10 CFR 63.342(c)(1)(i) specifies the seismic analysis may be limited to the effects caused by damage to the drifts in the repository, failure of the waste packages, and changes in the elevation of the water table under Yucca Mountain (i.e., the magnitude of the water table rise under Yucca Mountain).

## 5.2 Perspectives on Structural Performance of Engineered Barriers

DOE considered disruptive events (i.e., seismic events, fault movement, and accumulation of rock rubble in the repository drifts) that could affect the structural performance of the engineered barriers. In general, DOE estimated any significant damage would be limited and/or of very low probability of occurring. For example:

<u>Rupture of Drip Shield Plates due to Seismic Event</u>

*"DOE appropriately determined that a small likelihood exists for such ruptures if earthquakes with annual probabilities of exceedance of <$5 \times 10^{-7}$ occur. DOE adequately implemented this likelihood of plate failure in the TSPA."* (SER Vol. 3, page 5-29)

<u>Waste Package Breach due to Fault Movement</u>

*"SAR Table 2.3.4-59 showed that less than 2 percent of the waste packages can potentially be impacted by a seismic faulting event with an annual exceedance frequency of $1\times10^{-8}$/yr to $3\times10^{-8}$/yr. To mitigate the potential risk of faulting that could cause mechanical damage to the waste packages, DOE stated that waste packages would be placed 60 m [196.85 ft] from known, major faults (SAR Table 1.9.9, Design Control Parameter 01-05)."* (SER Vol. 3, pages 5-13 and 5-14)

<u>Waste Package Impacts due to Seismic Events (Intact Drip Shield)</u>

*"[t]he NRC staff concludes that impact velocities of 5 m/sec [16.4 ft/sec] are likely to occur only for seismic events with an APE of $10^{-8}$ or lower. Thus, subsequent seismic events capable of triggering these large impact velocities are unlikely and therefore beyond consideration for TSPA analyses. Moreover, the NRC staff also concludes that the waste package should have enough remaining capacity, after the first seismic event with impact velocities of 5 m/sec [16.4 ft/sec], to withstand subsequent seismic events at these impact velocities."* (SER Vol. 3, pages 5-37 and 5-38)

<u>Waste Package Puncture under Accumulated Rubble (failed drip shield plates)</u>

*"[t]he NRC staff determines that if DOE assumed that the waste package puncture probability exceeds zero for any deformation of the outer corrosion barrier, then the number of punctured waste packages during a seismic event at a 4.07-m/sec [13.35-ft/sec] PGV level would only increase by 2 percent. Moreover, because the APE for a 4.07-m/s [13.35-ft/sec] PGV level is $10^{-8}$, this difference in the waste package puncture probability during the postclosure period would reduce even further."* (SER Vol. 3, pages 5-45 and 5-46)

Stress corrosion cracking, due to seismic ground motion events, was estimated by DOE to damage most of the waste packages, however, it was also noted that this cracking is sufficiently narrow in size that the releases would be a diffusive release rather than advection as would be the case for larger damage areas (e.g., breaches and ruptures). [SER Vol. 3, page 5-30] In particular:

> *"The results of the seismic consequence abstractions are used as inputs to other process-level models and direct inputs to the TSPA. The waste package corrosion abstraction uses waste package breaches at the process level to initiate double-sided corrosion (reviewed in SER Section 2.2.1.3.1). Note that in this context, a breach is defined as any failure mechanism that penetrates the waste package (i.e., cracks, ruptures, and punctures). Waste package breaches also impact the chemistry inside the waste package (reviewed in SER Section 2.2.1.3.4). Stress corrosion crack area is used in the EBS transport abstraction to model a pathway for diffusive radionuclide release (reviewed in SER Section 2.2.1.3.4). Waste package rupture or puncture area is used in the flux-splitting model to calculate water flux through the waste package (reviewed in SER Section 2.2.1.3.3). Information presented in SAR Table 2.1-3 suggests that seismic ground motion damage to the EBS components is an important mechanism that affects the EBS capability to perform its intended functions. DOE stated in DOE (2009bl, Enclosure 1) that seismically-induced waste package damage is more significant in early times and that nominal failure processes are more significant at later times. According to DOE, seismically-induced stress corrosion cracking is the most probable waste package damage mechanism. The majority of commercial spent nuclear fuel (CSNF) and CDSP waste package failures due to seismically induced stress corrosion cracking occur prior to drip shield plate/crown failure, as described in DOE (2009bl, Enclosure 1, Figures 5 and 6)."* (SER Vol. 3, page 5-30)

## 5.3 Key Review Topics for Mechanical Disruption of Engineered Barriers

The structural performance of the drip shield is impacted by seismic events, fault movement, the accumulation of rock rubble inside the drifts, and potential interactions between the drip shield and waste package.

### 5.3.1 Seismic/Drift Stability as it Related to Mechanical Disruption

**1) DOE's Probabilistic Seismic Hazard Analysis (PSHA) methodology**

- NRC guidance on practical implementation guidelines for seismic hazard studies (NUREG-2117, NRC, 2012aa) – SER Vol. 3 page 5-5

- NRC branch technical position on expert elicitation (NUREG-1563, NRC, 1996aa) - SER Vol. 3 page 5-5

- NRC regulatory guidance REG GUIDE 1.165 (NRC 1997ab) and REG GUIDE 3.73 (NRC 2003ae) - SER Vol. 3 page 5-6

- NRC contractor independent geological and geophysical study (Stamatakos et al, 2007aa) - SER Vol. 3 page 5-6

- DOE response to NRC request for additional information regarding adequacy of DOE's method for conditioning of ground motion hazard (DOE 2009aq) – SER Vol. 3 page 5-8

- Report on recommendations for probabilistic seismic analysis regarding uncertainty and use of experts (Budnitz et al., 1997aa) – SER Vol. 3 page 5-5

- Input data used in expert elicitation on PSHA (CRWMS M&O 1998ab Appendix G; BSC 2004bp; Keefer et al. 2004aa; Spudich, et al., 1999aa) – SER Vol. 3 page 5-6

- New information available since DOE completed its expert elicitation (Hanks et al., 2013aa) – SER Vol. 3 page 5-9

**2) Seismically induced drift degradation**

- DOE report on rubble accumulation for different ground motion magnitudes (BSC 2004al) – SER Vol. 3 pages 5-15 and 5-16

- DOE response to NRC request for additional information regarding increased drift degradation due to such effects as thermal stress, multiple seismic events; and impacts to rubble accumulation (DOE 2010aa Enclosure 1) – SER Vol. 3 page 5-18

- DOE response to NRC request for additional information the bulking factor for rock rubble (DOE 2010ab Enclosure 1) – SER Vol. 3 page 5-20

- NRC contractor independent analysis of rock block sizes (Ofoegbu et al., 2007aa) - SER Vol. 3 page 5-20

**3) Seismic site response**

- Data for the seismic hazard curves (BSC 2008bl) – SER Vol. 3 page 5-10

- Procedures for ground motion input (McGuire, et al., 2001aa) – SER Vol. 3 page 5-10

**4) Fault Displacement Hazard Analysis**

- Probabilistic Fault Displacement Hazard Analysis (PFDHA) (CRWMS M&O 1998aa) – SER Vol. 3 pages 5-11 and 2-12

- NRC independent analyses of slip tendency (Morris et al., 1996aa; Morris et al., 2004aa) – SER Vol. 3 page 5-12

- NRC independent analyses of faulting (Waiting, et al., 2003aa; Ferrill, et al., 1999ab; Stamatakos, et al., 2007aa; NRC, 2005aa) – SER Vol. 3 page 5-6

### 5.3.2 Mechanical Disruption of the Drip Shield

The drip shield review included evaluation of its structural performance during the thermal period (i.e., the initial 12,000 years after closure) and the impact of geologic events (e.g., seismic events and fault movement).

1) **Drip shield structural/mechanical performance (seepage barrier function context)**

- The main structural elements of the drip shield consist of a framework that includes a bulkhead and support beams (legs) that will be made of Titanium Grade 29. Plates of Titanium Grade 7 are welded onto the framework to form a full composite structure in response to mechanical loading (SAR Section 2.3.4.5.1.1; SAR Figure 2.3.4-56) – SER Vol. 3 page 5-21

- Crack openings, such as those produced by stress corrosion cracking, are too small to allow advective flow of water through the drip shield and are excluded from the performance assessment analysis, as described in SNL (2008ab) for FEP 2.1.03.10.0B – SER Vol. 3 pages 5-21 to 5-22

- DOE concluded that seismically induced separations of drip shields can be excluded from the TSPA analysis on the basis of low probability (FEP 1.2.03.02.0A; SNL, 2008ab) – SER Vol. 3 page 5-22

- NRC staff reviewed the dynamic analyses in SNL (2007ay, Section 6.3.7.1) and confirmed that potential separations of the drip shield only occur in an open drift that is subjected to 5.35 m/sec [17.55 ft/sec] PGV ground motion – SER Vol. 3 page 5-22

- NRC independent confirmatory tests at elevated temperatures and calculations on drip shield deformation and drip shield deformation from rock loading (Ibarra et al., 2007aa) – SER Vol. 3 pages 5-24 and 5-26

- DOE response to NRC request for additional information on potential effects of temperatures greater than 120 C on titanium alloy properties (DOE 2009bp Enclosure 7) – SER Vol. 3 pages 5-24 to 5-25

- DOE response to NRC request for additional information on the uniformity of loads on the drip shield (DOE 2010ac) – SER Vol. 3 page 5-25

- DOE response to NRC request for additional information on representation of nonlinear responses of materials (DOE 2009bp Enclosure8) – SER Vol. 3 page 5-26

- DOE response to NRC request for additional information regarding drip shield rigidity to transfer loads to adjacent segments (DOE 2010ac) – SER Vol. 3 page 5-27

### 5.3.3 Mechanical Disruption of the Waste Package

The NRC staff review evaluated the potential disruption of the waste package under an intact drip shield as well as a collapsed drip shield.

1) **Waste package structural response with structurally stable drip shield**

- DOE response to NRC request for additional information regarding the assumption of an intact waste package pallet in waste package damage analyses (DOE 2009bq Enclosure 1) – SER Vol. 3 page 5-34
- DOE response to NRC request for additional information regarding acceptability of methodology that involves engineering judgment in qualitative evaluation of

waste package ruptures from for multiple impacts (DOE 2009bq Enclosure 2) – SER Vol. 3 page 5-37

- DOE response to NRC request for additional information regarding waste package strain (DOE 2009bq Enclosure 3) – SER Vol. 3 page 5-38
- DOE information on the most damaging scenario (SNL 2007ap) – SER Vol. 3 page 5-37

**2) Waste package structural response under a collapsed drip shield**

- DOE response to NRC request for additional information regarding damage for angular impacts on the waste package (DOE 2009br Enclosure 1) – SER Vol. 3 page 5-39

- NRC contractor independent analyses on the high ductility of Alloy 22 (Ibarra et al., 2007aa, ab; Pomerening et al., 2007aa) – SER Vol. 3 page 5-40

**3) Assessment of collapsed drip shield condition**

- NRC contractor independent analyses regarding tensile tearing of the waste package outer barrier (Ibarra et al., 2007ab) – SER Vol. 3 page 5-41

- DOE response to NRC request for additional information regarding the bounding nature of its results (DOE 2009bs) – SER Vol. 3 page 5-41

**4) Waste package structural response to direct contact with rubble**

- DOE response to NRC request for additional information regarding two-dimensional representation of waste package in seismic analyses (DOE 2009bt) – SER Vol. 3 page 5-43

- DOE response to NRC request for additional information regarding appropriateness of stress and strain computed at end of dynamic analysis (DOE 2009br Enclosure 2) – SER Vol. 3 page 5-45

- DOE response to NRC request for additional information regarding inconsistencies in reported stress threshold and damage area in SAR (DOE 2009bq Enclosure 4) – SER Vol. 3 page 5-46

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# 6.0 Quantity and Chemistry of Water Contacting the EBS

The degradation of engineered barriers as well as the release of radionuclides from the waste package are affected by the quantity of and chemistry of water that enters the repository drifts and contacts the engineered barriers.

> *"Safety Evaluation Report (SER) Section 2.2.1.3.3 provides the U.S. Nuclear Regulatory Commission (NRC) staff's evaluation of the U.S. Department of Energy's ("DOE" or the "applicant") abstraction of the repository drift system that may alter the chemical composition and volume of water contacting the drip shield and waste package surfaces (NRC, 2005aa). DOE described this abstraction in Safety Analysis Report (SAR) Sections 2.3.5 and 2.3.7 (DOE, 2008ab). The NRC staff's evaluation focuses on key features, events, and processes (FEPs) that address the following topics: (i) the chemistry of water entering the drifts, (ii) the chemistry of water in the drifts, and (iii) the quantity of water in contact with the engineered barrier system (EBS). These three abstraction topics provide the input needed to model the features and performance of the EBS (e.g., drip shield and waste package) and their contributions to barrier functions. For example, in its SAR, DOE relied on corrosion tests that were conducted on waste package and drip shield materials under a range of geochemical environments. The range of aqueous testing environments the applicant used was based on a range of potential starting water compositions and from knowledge of near-field and in-drift processes that alter these compositions."* (SER Vol. 3, page 6-1)

## 6.1 Requirements Specific to Quantity and Chemistry of Water

There are no requirements specific to the quantity and chemistry of water contacting engineered barriers and waste forms.

## 6.2 Performance Perspectives on Quantity and Chemistry of Water

> *"The NRC staff considers the following specific observations from DOE's performance assessment to be important in evaluating this abstraction of chemistry of water in the drifts:*
>
> - *During much of the thermal period, to about 12,000 years after repository closure, the drip shield is expected to prevent seepage water from contacting the waste package surface and greatly reduce the possibility of localized corrosion of the waste package.*
> - *With no seepage water contacting the waste package within 12,000 years after repository closure and relatively limited expected waste package corrosion, only diffusive, not advective, release of radionuclides from the waste package is considered possible by DOE.*
> - *For the period following 12,000 years after repository closure, DOE calculated that there is a low probability for the repository environment (i.e., pH and chemical composition of in-drift waters) to support localized corrosion of the waste package even if the drip shield fails and allows seepage water to contact the waste package.*

- *After 40,000 years, the temperature and relative humidity in the drifts is expected to have returned to conditions consistent with those prior to waste emplacement. Similarly, seepage water chemistry is also expected to have returned to compositions consistent with those prior to waste emplacement with dilute concentrations of dissolved components. As a result of the low temperature, high relative humidity, and dilute seepage water chemistry, localized corrosion is not an important contributor to waste package degradation after 40,000 years."* (SER Vol. 3, page 6-10)

As such, NRC concluded that aspects of the water chemistry limit potential degradation of engineered barriers, such as:

> *"The NRC staff concludes that, for temperatures consistent with environmental conditions prior to waste emplacement, the range of chemistry tabulated in the TSPA lookup tables (i.e., relative humidity; $pCO_2$ conditions of pH, ionic strength, and $Cl^-$ and $NO_3^-$ concentrations; and the $NO_3^-/Cl^-$ ratio) adequately represents the potential chemistry of water contacting the surface of waste packages and radionuclide transport in the invert. The NRC staff also concludes, on the basis of its independent analysis, that in-drift water chemistry is unlikely to initiate waste package localized corrosion in the time following 12,000 years after repository closure."* (SER Vol. 3, page 6-18)

Additionally, engineered barriers limit the quantity of water available for contacting waste for very long time periods. For example:

> *"In the TSPA model implementation, the average fraction of breached waste package surface area in 1 million years is on the order of $10^{-3}$ for the nominal and disruptive modeling cases. The applicant estimated that 0–11 percent (with a mean/median value of 5.5 percent) and 0–12 percent (with a mean/median value of 6 percent) of the seepage flux above the (failed) drip shield entered into a breached commercial spent nuclear fuel waste package for the nominal and seismic ground motion cases, respectively (DOE, 2009an)."* (SER Vol. 3, page 6-25

## 6.3 Key Review Topics for Quantity and Chemistry of Water

The NRC staff review evaluated the quantity of water contacting the engineered barriers, the chemistry of the water entering the drifts, and the relevant interactions with the engineered barrier materials (e.g., chemical interactions at elevated temperatures inside the drift)

**1) Quantity of water in contact with the engineered barrier system**

- DOE response to request for additional information regarding flow paths and fluxes in the engineered barrier system flow abstraction (DOE, 2009ab,an) - SER Vol. 3, pages 6-19 thru 6-22

- DOE response to request for additional information regarding dependence of water flow through a damaged package and area of breaches (i.e., corrosion patches) on waste package (DOE, 2009an) - SER Vol. 3, page 6-21

- DOE response to request for additional information on seeping conditions used for irreversible attachment of plutonium and americium onto mobile corrosion product colloids (DOE, 2009ay) - SER Vol. 3, page 6-22

- DOE report on breached drip shield experiments (BSC 2003ag) – SER Vol. 3, page 6-23

- NRC independent analyses estimating number of breached waste packages contacted by seepage flux (CNWRA and NRC 2008aa) – SER Vol. 3, page 6-25

**2) Chemistry of water in the drifts**

- A number of FEPs were excluded from further consideration (e.g., microbial activity in the engineered barrier system, radiolysis, chemical effects of excavation and construction in the engineered barrier system, chemical effects of rock reinforcement and cementitious materials in the engineered barrier system, and undesirable materials left in the repository) – SER Vol. 3, page 6-11

- DOE's response to request for additional information regarding the adequacy of characterization of the in-drift chemical environment (DOE, 2009cv,cw) - SER Vol. 3, pages 6-14 thru 6-17

- NRC independent modeling of in-drift processes and water (Murphy 1994aa; Browning, et al., 2004aa; Pabalan 2010aa) – SER Vol. 3, pages 6-13 and 6-14

- NRC staff independent modeling approach for in-drift water chemistry (Leslie, et al., 2007aa) – SER Vol. 3, page 6-17

**3) Chemistry of water entering drifts**

- DOE (2009dg, Enclosure 11) provided DOE's model results that both pH and nitrate-to-chloride ratio of water that might contact waste package is likely too high to initiate localized corrosion after 12,000 years – see SER Vol. 3 page 6-4

- DOE response to request for additional information regarding the adequacy of model inputs and conceptual model for chemistry of water entering the drift (DOE, 2009ck) see SER Vol. 3, pages 6-6 thru 6-8

- NRC independent analyses of environmental conditions affecting water chemistry (CNWRA, 2007aa; Pabalan, 2010aa) – see SER pages 6-4, 6-7 and 6-8

- NRC independent analyses of pore water samples (Pabalan, 2010aa) – see SER Vol. 3, page 6-7

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# 7.0 Radionuclide Release Rates and Solubility Limits

Release of radionuclides from the waste package will be affected by the release rates of radionuclides from the waste forms and the solubility limits for each of the radionuclides. Additionally, the chemical environment within the waste package may include colloids that any also affect the release of radionuclides.

> *"The engineered barrier system and the transport pathway within the drift (repository tunnel) are the initial barriers to aqueous radionuclide release. If a waste package is breached and water enters the waste package, the radionuclides contained in the package may be transported from the engineered barrier system. The processes that could lead to this radionuclide release are affected by the chemical characteristics of the water, which in turn are affected by the materials that interact with the water. Therefore, as required by 10 CFR 63.113 and 10 CFR 63.114, the performance assessment analysis models radionuclide release rates from the engineered barrier system because these rates would significantly affect the timing and magnitude of transport for any radionuclide released from the repository."* (SER Vol. 3, page 7-1)

> *"The output from the model of radionuclide release rates and solubility limits is used as input to the model for radionuclide transport in the unsaturated zone. The information the unsaturated zone model requires for calculating the movement of the radionuclides includes the rates and magnitudes of radionuclide release from the drift, including the characteristics of dissolved and colloidal species. Information from this model is also used for evaluating the barrier capability of the waste package interior, the waste form, and the drift below the waste package (e.g., the invert) and for supporting the scenario analysis for the engineered barrier system."* (SER Vol. 3, page 7-2)

## 7.1 Requirements Specific to Release Rates and Solubility Limits

No requirements specific to the release rates and solubility limits.

## 7.2 Performance Perspectives for Release Rates and Solubility Limits

The environment within the waste package has a significant impact on the release of radionuclides. The NRC staff review evaluated the key aspects affecting the release such as the conditions within the waste package, sorption and release onto colloids, and potential for greater colloidal releases for disruptive events with the potential to significantly impact the waste package (e.g., igneous event):

Environmental Conditions within the Waste Package

> *"The NRC staff finds that, in modeling the in-package chemical and physical environment, the applicant appropriately incorporated design features of commercial SNF and codisposal waste packages. The applicant used appropriate conceptual and mathematical models and assumptions to simulate geochemical interactions between fluids, gases, and internal components of the waste package and generate abstractions for pH, ionic strength, and*

*fluoride concentration. The applicant used sufficient and technically defensible data to establish initial and boundary conditions for model simulations. These data included the thermodynamic properties of solids, gases, and aqueous species; incoming water chemistries; and the compositions, surface areas, and degradation rates of waste forms and material components of the waste package. The NRC staff finds that model simulations were appropriately applied over the full range of environmental conditions that might be expected inside breached waste packages."* (SER Vol. 3, pages 7-12 and 7-13)

<u>Colloid Release and Sorption</u>

*"TSPA release rates for radionuclide transport in the engineered barrier system vary significantly by radionuclide and modeling case. The engineered barrier system does not significantly delay transport of soluble, nonsorbing radionuclides, such as Tc-99 and I-129, and the waste package failure rates control the engineered barrier system release rates for those radionuclides. Transport of low-solubility, sorbing radionuclides, such as Np-237 and Pu-242, is significantly slower and is generally controlled by sorption onto stationary corrosion products and precipitation of radionuclide-bearing minerals in the corrosion products domain. Colloid-assisted transport is not significant compared with transport of dissolved radionuclides because of limited colloid concentrations in the engineered barrier system. The NRC staff finds that the TSPA code results for the engineered barrier system release rates are consistent with the NRC staff's simplified confirmatory calculations, confirming the appropriateness of the TSPA results."* (SER Vol. 3, page 7-50)

<u>Colloid Release and Sorption for Disruptive Events</u>

*"The applicant provided information showing that engineered barrier system releases of low-solubility, sorbing radionuclides (e.g., plutonium and neptunium) are mainly controlled by processes within the corrosion products domain because waste form dissolution and invert transport processes are fast, relative to transport within the corrosion products domain. In the TSPA analyses, the important dose contributions from plutonium and neptunium isotopes result from the igneous intrusion modeling case (SAR Section 2.4.2.2.1.1.3), in which all waste packages fail and releases of these radionuclides are controlled by advection modified by sorption and precipitation of radionuclide-bearing minerals. The NRC staff performed simplified estimates to confirm the applicant's release calculations for Pu-242 and Np-237 for the igneous intrusion modeling case in the engineered barrier system. The NRC staff assumed that these release rates for the corrosion products domain are controlled by advection and either (i) precipitation of solubility-limiting minerals or (ii) sorption onto corrosion products. The solubility limit (SER Section 2.2.1.3.4.3.3) is a chemically-based maximum value for the dissolved concentration of an element, in the absence of sorption. If, however, there is capacity for sorbing the dissolved element onto solid surfaces, the dissolved concentration may not reach the solubility limit and could be controlled to a lower value by sorption (SER Section 2.2.1.3.4.3.5). Because both solubility and sorption are viable processes in the corrosion products domain, the better estimate of release rate is obtained by calculating release based on the process that limits the dissolved concentration to the lowest value. The NRC staff therefore, used simplified calculations to estimate release rates controlled by both potential limits on dissolved concentration—solubility and sorption—and selected the lower value of the two for comparison to the applicant's results."* (SER Vol. 3, pages 7-48 and 7-49)

## 7.3 Key Review Topics for Release Rates and Solubility Limits

The NRC staff review evaluated the environment within the waste package and its impact on waste form degradation and release rates of radionuclides from the waste form, including effects on concentration limits and potential colloid-facilitated release. In addition, the staff evaluated the DOE abstraction of transport of radionuclides from the waste form and out of the EBS.

**1) Waste form degradation**

- DOE response to request for additional information that characteristics of commercial spent nuclear fuel will not be altered during transportation and interim storage (DOE,2009ax, Enclosure 3) - SER Vol. 3, page 7-15

- NRC independent analyses regarding $UO_2$ matrix behavior in an oxidizing environment and spent nuclear fuel dissolution kinetics (Leslie, et al., 2007aa; NRC, 2008aa) – SER Vol. 3, page 7-16

- NRC independent analyses of the environmental conditions inside the waste package (Leslie, et al., 2007aa; NRC, 2008aa, 1996ab) – SER Vol. 3, page 7-16

- DOE response to request for additional information regarding dissolution in pure carbonate solutions causing increased actinide release associated with colloids (DOE,2009ax, Enclosure 16) - SER Vol. 3, page 7-17

- NRC staff evaluation of information on high-level waste glass degradation (Leslie et al., 2007aa) – SER Vol. 3, page 7-18

- DOE response to request for additional information regarding colloid concentrations from waste form degradation under disruptive scenarios (DOE,2009ax, Enclosure 1; DOE,2009cz, Enclosure 1; DOE,2009db, Enclosure 1) - SER Vol. 3, pages 7-20 and 7-21

- DOE response to request for additional information regarding colloid concentrations from waste form degradation in the nominal scenario (DOE,2009ax, Enclosure 16) - SER Vol. 3, page 7-21

- BSC (2004ah,ai) showing no indication of microbe effects reported in literature data – SER Vol. 3, page 7-22

**2) Availability and effectiveness of colloids**

- SNL 2008ag provides concentration ranges for colloid concentrations resulting from glass waste, commercial SNF, oxidized uranium, and groundwater – SER Vol. 3, page 7-31

- SNL 2008ak describes the abstraction of colloid-facilitated radionuclide release, including description of colloids associated with degradation of borosilicate glass and iron oxides – SER Vol. 3, pages 7-30 through 7-38

- DOE response to request for additional information regarding disruptive modeling cases and processes and features that could limit availability and transport of colloids (DOE,2009ay, Enclosure 3) - SER Vol. 3, page 7-34

- DOE response to request for additional information regarding plutonium sorption onto stationary corrosion products (DOE,2009ay, Enclosures 2 and 8; and DOE, 2009da, Enclosure 1, Figures 5 and 7) - SER Vol. 3, pages 7-34 and 7-35

- NRC independent confirmatory calculation for plutonium attachment rate to iron oxide colloids (Pickett, 2010aa) – SER Vol. 3, page 7-34

**3) Engineered Barrier System radionuclide transport**

- DOE response to request for additional information regarding the retention of radionuclides on waste package corrosion products (DOE 2009da, dc) – SER Vol. 3, page 7-40

- DOE response to request for additional information regarding releases from the engineered barrier system for stable and unstable waste form colloids (DOE,2009dc; DOE,2009da, Enclosure 1) - SER Vol. 3, page 7-42

- DOE response to request for additional information regarding limited effect of assumed relative abundance of hydrous ferric oxide (DOE,2009ay, Enclosure 6) - SER Vol. 3, page 7-44

- DOE responses to requests for additional information regarding radionuclide sorption coefficients for corrosion products (DOE 2009ay Enclosure 9; DOE 2009da Enclosure 3) – SER Vol. 3, page 7-45

- DOE response to request for additional information showing sorption in the corrosion product domain is approximately an equilibrium process due to water residence time (DOE,2009ay, Enclosure 8) - SER Vol. 3, page 7-46

- DOE response to request for additional information regarding colloid stability in corrosion product domain (DOE,2009ay) - SER Vol. 3, page 7-48

- NRC independent evaluation of radionuclide sorption (Leslie, et al., 2007aa) – SER Vol. 3, page 7-45

- NRC independent confirmatory calculations of engineered barrier system releases radionuclide sorption (Painter 2010aa and Pickett 2010aa) – SER Vol. 3, pages 7-48 thru 7-50

- NRC independent analyses regarding colloid facilitated transport (Cvetkovic, et al., 2004aa; Painter and Cvetkovic, 2006aa) – SER Vol. 3, page 7-47

**4) In-package Chemical and physical environment**

- DOE response to request for additional information regarding effect of waste package design for HLW glass does not affect pH limits (DOE,2009ax, Enclosure 4) - SER Vol. 3, page 7-10

- DOE report on effects of flow conditions on in-package water chemistry [BSC 2005ad, Section 6.6.1(a)] – SER Vol. 3, page 7-5

- Report on representative water compositions for potential incoming water chemistry (Harrar, et al., 1990aa) – SER Vol. 3, page 7-7

- DOE report showing limited sensitivity of in-package chemistry to incoming water composition in BSC [2005ad Sections 6.5(a) and 6.6(a)] and in SAR Figures 2.3.7-13 through 2.3.7-18 – SER Vol. 3, page 7-7

- SNL (2007ak, Section 6.6.5) providing the range of predominant water types found in Topopah Spring welded tuff unit – SER Vol. 3, page 7-7

- DOE report showing sensitivity of liquid influx rate and material degradation on in-package ionic strength (BSC 2005ad Sections 6.6.4[a] and 6.6.5[a]) – SER Vol. 3, page 7-11

**5) Concentration limits**

- DOE response to request for additional information regarding the corrosion products and the chemical environment in the waste package (DOE 2009ax Enclosure 7; DOE 2009ay Enclosure 3; DOE 2009da Enclosure 2; and DOE 2009db Enclosure 3) – SER Vol. 3, pages 7-24 and 7-25

- DOE response to request for additional information regarding plutonium and neptunium solubility models (DOE,2009ax, Enclosures 8, 9, and 12; DOE,2009cz, Enclosures 5, 6 and 7) - SER Vol. 3, page 7-26

- Solubility-limiting phases for actinides based on available data and from the literature and the Yucca Mountain program (SNL, 2007ah) – SER Vol. 3, pages 7-27 and 7-28

- DOE response to request for additional information regarding dissolved concentrations in the engineered barrier release domains (DOE 2009dc) – SER Vol. 3, page 7-29

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# 8.0 Climate and Infiltration

Climate and infiltration affects the quantity of water that can affect the net infiltration that is available to contact breached waste packages and transport radionuclides out of the EBS.

> *"DOE considers the reduction of water flux from precipitation to net infiltration to be a barrier capability for the Upper Natural Barrier. Because of the generally vertical movement of percolating water through the unsaturated zone in the DOE representation of the natural system, water entering the unsaturated zone at the ground surface (infiltration) is the only source for deep percolation water in the unsaturated zone at and below the proposed repository."* (SER Vol. 3, page 8-1)

> *"Climate and infiltration are treated differently in DOE's performance assessment for the initial 10,000 years of the repository and the period from 10,000 to 1 million years. For the initial 10,000 years, DOE used paleoclimate records for the region to predict future climatic conditions and uses these predictions as input for estimating future net infiltration…For the period from 10,000 years to 1 million years after disposal, 10 CFR 63.342(c)(2) allows the applicant to consider long-term-average deep percolation flux at the proposed repository horizon instead of explicitly predicting climate and infiltration. DOE chose to use the prescribed deep percolation flux in its performance assessment for the post-10,000-year period."* (SER Vol. 3, page 8-1)

## 8.1 Requirements Specific to Climate and Infiltration

*"The requirements in 10 CFR 63.342(c)(2) pertain to the use of specified constant-in-time deep percolation rates to account for the effects of climate change on performance for the period from 10,000 to 1 million years after disposal. The NRC staff's evaluation of the applicant's use of these deep percolation rates is given in SER Section 2.2.1.3.6.3.2.*

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*The following requirements for characteristics of the reference biosphere to be used in this abstraction for climate and infiltration are specified in 10 CFR 63.305:*

- *FEPs that describe the reference biosphere must be consistent with present knowledge of the conditions in the region surrounding the Yucca Mountain site. [10 CFR 63.305(a)]*

- *DOE should not project changes in society, the biosphere (other than climate), or human biology or increases or decreases of human knowledge and technology; in all analyses done to demonstrate compliance with this part, DOE must assume that all of those factors are constant as they are at the time of submission of the license application. [10 CFR 63.305(b)]*

- *DOE must vary factors related to the geology, hydrology, and climate based upon cautious but reasonable assumptions of the changes in these factors that could affect the Yucca Mountain disposal system during the period of geologic stability*

*[10 CFR 63.305(c)], which for the climate and infiltration abstraction is limited to the initial 10,000 years after disposal*

- *Biosphere pathways must be consistent with arid or semi-arid conditions. [10 CFR 63.305(d)]*

*The requirements of 10 CFR 63.305 apply to the abstraction reviewed in this SER Section to the extent that the characteristics of the reference biosphere affect climate and infiltration."* (SER Vol. 3, pages 8-2 and 8-3)

## 8.2 Performance Perspectives for Climate and Infiltration

Estimating the amount of water that can reach the repository begins with the climate and infiltration.

*"DOE described the present climate at Yucca Mountain as semi-arid, with low annual precipitation. DOE expects the climate to change over the initial 10,000 years, remaining semi-arid but with changes in precipitation patterns and rates. DOE recognized that surface temperature and vegetation will also vary with changes in climate. Evapotranspiration (the combination of evaporation and plant transpiration) removes a large portion of the annual precipitation that infiltrates into the soil. In this environment, evapotranspiration is strongly influenced by temperature and low atmospheric relative humidity. In DOE's conceptual model, net infiltration events occur in pulses during and for a short period following some of the larger or longer duration precipitation events. Evapotranspiration continually dries the soil between precipitation events."* (SER Vol. 3, page 8-4)

*"In determining the significant aspects of DOE's net infiltration model, NRC staff considered how the flux of water through the unsaturated zone affects (i) seepage (flux of water dripping into drifts), (ii) release of radionuclides from the engineered barrier system, and (iii) radionuclide transport through the natural system."* (SER Vol.3, page 8-2)

## 8.3 Key Review Topics for Climate and Infiltration

The NRC staff review evaluated the climate and infiltration models by considering the range of considered climatic conditions and corresponding infiltration rates above the repository footprint. The review topics are presented with respect to (i) the climate data for present conditions, (ii) the future climate model, and (iii) the net infiltration model that converts climate into deep percolation.

In semiarid locations such as the Yucca Mountain region, significant infiltration is episodic and occurs in favored spatial locations, during unusually wet events that allow rapid wetting pulses to escape below the evapotranspiration (ET) zone over a few days to weeks. At Yucca Mountain, ET escape generally occurs when the wetting pulse enters fractures in the bedrock, which is favored by (i) shallow soil over fractured bedrock and (ii) overland flow locally increasing infiltration fluxes. Accordingly, the key performance aspects are related to quantifying (i) where wetting pulses can escape ET, (ii) how climate change affects the intensity, duration, and frequency of precipitation events and how soil and vegetation are affected in turn, and (iii) likely ranges of climate change.

1) **Net Infiltration Models and Soil Property Inputs**

- SNL (2007az Sections 6.2, 6.3 and 6.4) description and support for key Mass Accounting System for Soil Infiltration and Flow (MASSIF) model elements for climate and meteorology, subsurface water movement and storage, surface runoff and run on, evapotranspiration (SER Vol. 3, pages 8-16 and 8-17)

- DOE response to request for additional information regarding impact of spatial variability in net infiltration (DOE,2009cr, Enclosure 4) - SER Vol. 3, page 8-18

- DOE response to request for additional information regarding the effect of soil thickness uncertainty for areas of thin soils on estimates of net infiltration (DOE,2009cr, Enclosure 5) - SER Vol. 3, pages 8-19 and 8-20

- DOE response to request for additional information regarding water holding capacity for local Yucca Mountain soils (DOE,2009cr, Enclosure 6) - SER Vol. 3, page 8-20

- DOE response to request for additional information regarding impact uncertainty in spatial and temporal distribution of net infiltration on performance (DOE,2009bo, Enclosure 5; DOE 2009cr, Enclosure 4) - SER Vol. 3, pages 8-20 and 8-24

- DOE response to request for additional information regarding changes to soil depth and properties under future climates (DOE,2009cr, Enclosure 2) - SER Vol. 3, page 8-21

- NRC independent model for net infiltration in arid environments (Stothoff and Walter 2013aa; Stothoff 2013aa,ab; Stothoff 2008aa; Stothoff and Musgrove 2006aa). (SER Vol. 3, page 8-17)

- NRC independent model for runoff and infiltration (Woolhiser et al. 2000aa and 2006aa). (SER Vol. 3, page 8-18)

- NRC independent data on soil depths and field investigations (Fedors 2007aa; and Stothoff 2008ab) – SER Vol. 3, pages 8-19 and 8-20

2) **Temporal Variability in Meteorological Parameters**

- SNL (2007az Appendix F) presents DOE's representation of precipitation for winter and summer precipitation for potential future climate states (SER Vol. 3, page 8-15)

- NRC independent analysis of cool-season (winter) and warm season precipitation impact on net infiltration (Stothoff and Walter 2013aa; Stothoff 2013aa,ab) (SER Vol. 3, page 8-14)

- NRC independent evaluation of mean and summer precipitation for potential future climate states (Stothoff 2010aa). (SER Vol. 3, page 8-15)

- NRC independent evaluation of temperature (Stohoff 2008aa, Figures 5-8 and 5-9). (SER Vol. 3, page 8-15)

**3) Spatial Variability in Meteorological Parameters**

- DOE cited regional studies in SNL (2007az, Sections 6.4.11 and 6.4.5.3) indicating that mean annual precipitation and mean annual temperature are correlated with elevation even though local topography can modify the relationship. (SER Vol. 3, page 8-13)

- NRC independent analysis confirmed DOE precipitation lapse rate is comparable to other regional relationships, within the bounds of uncertainty, over an elevation difference typical of the repository footprint (Stothoff, 2008aa). (SER Vol. 3, page 8-14)

**4) Timing and Duration of Climate States (present-day, monsoon, and glacial-transition) in the initial 10,000 years**

- DOE described the use of the Forester, et al. (1999aa) analysis of river flow data and ostracode occurrences from Owens Lake to construct past climates for glacial stages that are consistent with Earth-orbital parameters and local paleoclimatic data (SER Vol. 3, page 8-6)

- Potential for an early transition to a full-glacial climate state has low probability of occurring during the initial 10,000 years - DOE estimates a return to a full-glacial climate state 30,000 years (SAR Section 2.3.1.2.1.2.3) after permanent closure. (SER Vol. 3, page 8-9)

- The transition between present-day and monsoon climate states, as set by DOE at 600 years following closure has low consequence - DOE estimated that above-boiling conditions within emplacement drifts may persist for several hundred to more than 1,000 years, depending on a number of factors such as emplacement drift location (SAR Section 2.3.3.3.3.1). (SER Vol. 3, page 8-8)

- Transition between monsoon and glacial transition climate states has low consequence on performance assessment results – mean annual infiltration values for these two climate states are similar (calculated weighted-average mean annual infiltration values over the repository footprint for the monsoon and glacial-transition climate states of 15.88 and 21.25 mm/yr [0.625 in/yr and 0.837 in/yr], respectively, as shown in DOE (2010ai, Enclosure 1,Table 1); and concurrently increasing areal-average mean annual infiltration by a factor of 2.39 for the monsoon state and 1.81 for the glacial-transition state has little effect on performance assessment results, as described in DOE (2009bo, Enclosure 5).

- NRC staff understanding of paleoclimatic data and approaches for projecting future climates (Stothoff and Walter 2013aa) (SER Vol. 3, page 8-7)

**5) Uncertainty in Climatic Conditions During the Post-Thermal-Pulse Period**

- DOE representation of bounding climatic conditions (SAR Section 2.3.1.2.3.1.2) and bounds for annual precipitation (SAR Table 2.3.1-6) (SER Vol. 3, page 8-10)

- NRC independent information on glacial maximum published estimates for mean annual precipitation in the region surrounding Yucca Mountain (Stothoff and Walter 2013aa)

**6) Uncertainty in Climatic Conditions from Anthropogenic Activities**

- DOE (2009cr, Enclosure 8) considered projected climate changes in the desert Southwest, described by the International Panel on Climate Change (Christensen, et al., 2007aa) as likely warmer with a decrease in annual preciptation [the NRC staff notes that the climate change projected by Christensen, et al. (2007aa) is similar but smaller than that used by DOE for a switch from present-day to monsoonal climate]- (SER Vol. 3, page 8-11)

- Cayan, et al. (2013aa) project little change in annual precipitation and less than 3 percent increase in winter precipitation for southern Nevada under the worse of two scenarios of greenhouse gas emissions. (SER Vol. 3, page 8-12)

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# 9.0 Unsaturated Zone Flow

The unsaturated zone above the repository affects the flow of water to the repository drifts that can enter the drifts via dripping water and the unsaturated zone below the repository affects the transport of radionuclides from the EBS to the saturated zone below the repository.

> *"Safety Evaluation Report (SER) Section 2.2.1.3.6 provides the U.S. Nuclear Regulatory Commission (NRC) staff's evaluation of the U.S. Department of Energy's ("DOE" or "applicant") abstraction of groundwater flow in the portion of the repository system above the water table. DOE presented this information in its Safety Analysis Report (SAR) of June 3, 2008 (DOE, 2008ab) and subsequent update of February 19, 2009 (DOE, 2009av)."*
> (SER Vol. 3, page 9-1)
>
> *"The proposed Yucca Mountain repository site has up to 400 m [1,300 ft] of variably saturated rock between the ground surface and the repository and at least 200 m [650 ft] between the repository and the underlying water table (SAR Sections 2.1.1.1 and 2.1.1.3). Water percolating through the unsaturated zone may enter the drifts, thereby providing the means to interact with and potentially corrode the waste packages. DOE defined seepage as the water entering the drifts via dripping from the drift ceiling (SAR Section 2.3.3.2.1). Water percolating through the unsaturated zone below the repository also provides flow pathways for transporting radionuclides downward to the water table."*
> (SER Vol. 3, page 9-1)
>
> In this section, *"the term "unsaturated zone" flow includes not only flow processes in the host rock under ambient and thermally perturbed conditions, but also in-drift hydrological processes related to flow through natural rubble and in-drift convection and condensation."*
> (SER Vol. 3, page 9-1)

## 9.1 Requirements Specific to Unsaturated Zone Flow

There were no requirements specific to unsaturated zone flow, however, as noted in the previous section (Section 8 Climate and Infiltration) it was explained that *"[T]he requirements in 10 CFR 63.342(c)(2) pertain to the use of specified constant-in-time deep percolation rates to account for the effects of climate change on performance for the period from 10,000 to 1 million years after disposal"* (SER Vol. 3, page 9-3). Thus, unsaturated zone flow rates are conditioned on the percolation rates for the period from 10,000 to 1 million years, as specified in the regulations.

## 9.2 Performance Perspectives for Unsaturated Zone Flow

*"The unsaturated zone plays a role in two of the DOE-defined barriers: the Upper Natural Barrier and the Lower Natural Barrier (SAR Section 2.3.2). These barriers are reviewed in SER Section 2.2.1.1.3.2. Together with Climate and Infiltration (reviewed in SER Section 2.2.1.3.5), processes in the unsaturated zone above the repository comprise the Upper Natural Barrier. They influence system performance through the amount of water reaching the Engineered Barrier System and their control on hydrological conditions in the drift. In DOE's model of the nominal scenario, the Quantity and Chemistry of Water Contacting Engineered Barriers and Waste Forms (reviewed in SER Section 2.2.1.3.3), Degradation of Engineered Barriers (reviewed in SER Section 2.2.1.3.1), and Radionuclide Release Rates and Solubility Limits (reviewed in SER Section 2.2.1.3.4) abstractions use in-drift liquid water, relative humidity, and temperature to assess the potential for corrosion of waste packages, release of waste, and transport to the natural system. In the disruptive scenarios of seismic and igneous intrusion (reviewed in SER Sections 2.2.1.3.2 and 2.2.1.3.10), DOE's model uses the flux of water to assess the movement of radionuclides to the natural system below the repository. The portion of the unsaturated zone below the repository is part of the Lower Natural Barrier. The magnitude and distribution of flux in the unsaturated zone below the repository are used to determine the flow pathways for Radionuclide Transport in the Unsaturated Zone (reviewed in SER Section 2.2.1.3.7). The unsaturated zone below the repository links the repository Engineered Barrier System to the Saturated Zone Flow and Transport System (reviewed in SER Sections 2.2.1.3.8 and 2.2.1.3.9) and ultimately to the biosphere in the accessible environment (reviewed in SER Sections 2.2.1.3.12 to 2.2.1.3.14)."* (SER Vol. 3, pages 9-1 and 9-2)

The unsaturated zone above the repository impacts the spatial and temporal flow of water into the repository drifts in terms of the seepage flux and seepage fraction (i.e., the portion of the repository where dripping is expected to occur – essentially the same as the number of waste packages getting wet). (SER Vol. 3, page 9-36)

*"Two primary processes provide barrier capability in DOE's seepage model: capillary diversion of liquid water around large openings (drifts in this case) and vaporization in the host rock that creates a dry zone around the drifts (SAR Section 2.1.2.1). Capillary forces may make drifts barriers to flow by inducing water to laterally flow (divert) around the large opening. During the thermal period, the vaporization barrier refers to the boiling of water in the host rock and migration of the resultant vapor to locations away from the heat source. In DOE's abstraction, the resultant creation of a dryout zone surrounding a drift leads to elimination of liquid flux at the drift wall."* (SER Vol. 3, page 9-31)

*"In the DOE abstraction, seepage fraction is important because releases of radionuclides in the seeping environment are transported by advection. In that portion of the repository where the liquid flux is zero, any released radionuclides are transported by diffusive processes out of the waste package, which are slow compared to advective transport rates. Releases in the nonseeping environment rely on transport by diffusion along stagnant water films. Therefore, determination of the threshold at which seepage occurs can impact radionuclide transport."* (SER Vol. 3, page 9-37)

*“The NRC staff concludes that seepage fractions are not underestimated on the basis of the following*

- *For the 10,000-year period, DOE adequately demonstrated that drip shields are estimated to remain intact significantly beyond the initial 10,000 years (SER Sections 2.2.1.3.1.3.1 and 2.2.1.3.2.6). Therefore, no liquid is predicted to reach the waste packages because drip shields divert all water regardless of whether the drift segment is a seeping or nonseeping environment. Therefore, the average value, and any uncertainty, in the value of seepage fraction are not important for performance during the initial 10,000 years.*

- *For the million-year period, the NRC staff notes that the calculated seepage fractions cannot increase much before reaching the bounding value of one (i.e., all waste packages get wet). Increasing the seepage fraction from 0.69 to the maximum of 1 at most results in a 44 percent increase in dose, assuming all aspects of release and travel paths are the same for the additional area compared to the original area. This increase in dose is not significant to performance results as total dose is not close to the criteria specified in 10 CFR Part 63; the NRC staff found in SER Section 2.2.1.4.1 that estimated dose is significantly less than the standards in 10 CFR Part 63.”* (SER Vol. 3, page 9-37)

The transport of radionuclides in the unsaturated zone below the repository is influenced on the location in the repository where the releases occur due to spatial variability of the flow paths in the unsaturated zone below the repository. Generally, the released radionuclides will be transported vertically downward to the saturated zone; however, the flow paths can be either in fractures or the porous matrix depending on the release point over the footprint of the repository.

*“Flow path differences between the northern and southern portions of the repository influence the travel times of non-sorbing and sorbing radionuclides. DOE provided model results (SAR Figures 2.3.8-36 and 2.3.8-49) that showed three predominant types of transport pathways. These are (i) fast transport for fracture releases occurs in the northern half of the repository, with mean travel times of years to centuries; (ii) moderately slow transport pathways for both matrix and fracture releases go through the southern half of the repository, with mean travel times of centuries to millennia; and (iii) slow transport through the matrix for radionuclides released into the matrix of the TSw tuff with mean travel times of millennia, with a small percentage transferring to the fracture system and reaching the water table more rapidly. The DOE ambient site-scale unsaturated zone model includes perching below the repository horizon in the northern half of the repository. In the DOE implementation, perching diverts fracture waters into faults and thereby creates a large difference in travel times for the northern and southern halves of the repository.”*
(SER Vol. 3, page 9-56)

## 9.3 Key Review Topics for Unsaturated Zone Flow

The NRC staff review evaluated the unsaturated zone flow models over the range of processes and features occurring at widely disparate spatial and temporal scales that affect flow fields above and below the repository, seepage into drifts, and the thermal environment. The review topics are presented with respect to (i) unsaturated flow above the repository affecting seepage into the drifts, (ii) thermal impacts affecting the seepage and flow near the repository, and (iii) unsaturated flow beneath the repository affecting transport of radionuclides to the saturated zone.

Possibly one of the most important performance aspects of a repository in a semi-arid location is the fraction of rainfall that is lost to evapotranspiration, which therefore limits the amount of water that can contribute to net infiltration (or deep percolation). Table 9-1 of the SER illustrated the quantitative reduction in flux from the ground surface to water entering the drift using flux averages over the repository footprint (flux values were obtained from DOE 2010ai, Enclosure 1, Tables 1, 5, and 8). Flow focusing in space and time may also be risk significant, by affecting (i) the fraction of waste packages that intercept flow, (ii) percolation thresholds (such as seepage into drifts), and (iii) travel times for released radionuclides from the repository horizon to the water table.

**Table 9-1. Quantitative Reduction in Flux From the Ground Surface to Water Entering the Drift Using Flux Averages Over the Repository Footprint**

| | Precipitation mm/yr* | Net Infiltration mm/yr* | Unsaturated Zone Site-Scale Top Boundary Net Infiltration mm/yr* | Deep Percolation mm/yr* | Seepage Repository Footprint | |
|---|---|---|---|---|---|---|
| | | | | | Flux mm/yr* | Fraction of Area |
| Component of Upper Natural Barrier | — | Topography and Soils | — | Unsaturated Zone | Unsaturated Zone | |
| Primary Feature or Processes | Semiarid Climate | Evapotranspiration, Runoff, Infiltration | Uncertainty in Net Infiltration | — | Capillary Diversion and Vapor Barrier | |
| Section of SAR | 2.3.1 | 2.3.1 | 2.3.2 | 2.3.2 | 2.3.3 | |
| Thermal Period † | — | — | — | — | 0 | 0 |
| Initial 10,000 years, Nominal ‡ | 296.7 | 38.88 | 21.37 | 21.74 | 2.0 {6.4} § | 0.31 |
| Initial 10,000 years, Seismic ‡ | | | | | 2.3 {7.4} § | 0.31 |
| Post-10,000 years Nominal | — | — | — | 31.83 | 3.4 {8.5} § | 0.40 |
| Post-10,000 years, Seismic | | | | | 15.5 {22} § | 0.69 |

*Units: 25.4 mm/yr = 1 in/yr

† Thermal period defined by drift wall temperature > 100 °C [212 °F] (SAR Section 2.3.3.3.4).

‡ Values of precipitation and percolation for initial 10,000 years are for glacial transition climate.

§ Average flux for seeping environment is in brackets

### 1) Unsaturated zone flow above the repository affecting seepage

- DOE consistently identified the net infiltration as significant to drift seepage and releases from the repository (SNL 2008ag) and to a lesser extent the impact of uncertainties in rock properties and in-drift temperatures affecting seepage into drifts (SNL 2008ag, Section K4) – SER Page 9-10

- NRC independent analyses for development of model input sets for different needs of infiltration and unsaturated zone models (Stothoff 2013aa,ab; Manepally et al. 2004aa) (SER Vol. 3 Page 9-13)

- DOE response to request for additional information regarding statistical distribution of intermediate- and fine-scale fluxes and performance assessment calculations showing limited sensitivity to intermediate scale fluxes (DOE 2009bo enclosures 4 and 2) (SER Vol. 3 page 9-14)

- DOE response to request for additional information regarding weighted-average infiltration over the repository footprint (DOE 2010ai enclosure 1) (SER Vol. 3 page 9-18)

- DOE response to request for additional information regarding exclusion of FEP 2.2.07.05.0A - episodic infiltration (DOE 2009an enclosure 2) (SER Vol. 3 page 9-19)
- DOE response to request for additional information regarding on the limited impact of long-term fluctuations on seepage (DOE 2009bo enclosure 5; DOE 2009cc enclosure 1) and NRC independent analyses (Stothoff 2010aa section 3; and Stothoff and Walter 2013aa Table 4-2) (SER Vol. 3 pages 9-19 and 9-20)

- DOE response to request for additional information regarding limited impact of spatial variability (DOE 2009bo enclosure 4 and 2009cx enclosure 1) (SER Vol. 3 page 9-20)

- DOE response to request for additional information regarding the limited impact of the proposed and final rule containing different percolation distributions (DOE 2009cb enclosure 6) (SER Vol. 3 page 9-22)

**2) Thermohydrologic modeling**

- DOE used its Drift Scale Test and Large Block Test to support the thermohydrologic models and estimates (SAR Section 2.3.5.4.1.3.3 and SNL 2008aj Sections 7.3 and 7.4) – SER Vol. 3 page 9-25

- NRC independent analyses of thermohydrologic processes at Yucca Mountain (NRC 2005aa; Painter et al. 2001aa; Manepally, et al. 2004aa) (SER Vol. page 9-25)

- DOE modeling analyses associated with thermohydrologic processes impacted releases (SNL 2008ag e.g. Sections 6.3.2.2 and 7.3.4.3.1) (SER Vol. 3 page 9-27)

- DOE screened out thermohydrologic processes related to engineered components such rock bolts and associated boreholes for ground support – SER noted screening arguments with respect to FEP 1.1.01.01.0B (Influx through Holes Drilled in Drift Wall or Crown) and 2.1.06.04.0A (Flow Through Rock Reinforcement Materials in Engineered Barrier System) were acceptable in SER Section 2.2.1.2.1.1 – SER Vol. 3 page 9-27

- DOE screened in mechanisms of drift degradation from seismic-induced ground motion, including in-drift temperature and relative humidity consequences from seismic-induced drift collapse. DOE expects that, under bounding assumptions, peak waste package temperatures for some waste packages may exceed the design basis temperature by nearly 100 °C [180 °F] if drifts were to collapse within the first 90 years after closure (SAR Section 2.3.5.4.3, SAR Figure 2.3.5-37). (SER Vol. 3, page 9-30)

**3) Ambient and Thermal Seepage Models**

- DOE described the capillary diversion of liquid water around large openings and vaporization in the host rock that creates a dry zone around drifts (SAR Section 2.1.2.1) – SER Vol. 3 page 9-31

- DOE's injection tests at Yucca Mountain form the basis of DOE's calibrated seepage model (BSC 2004av Section 6.2 – SAR Section 2.3.3.2.3.3) – SER Vol. 3 page 9-33
- NRC understanding of seepage-related features and processes at Yucca Mountain obtained from field observations and independent analyses (NRC 2005aa; Leslie et al. 2007aa; Basagaoglu et al. 2007aa; Or et al. 2005aa) (SER Vol. 3 page 9-34)

- DOE response to request for additional information regarding modeling uncertainties in capillary diversion to reduce seepage into drifts (DOE 2009ct enclosures 2 and 4; DOE 2009bo enclosure 1; and DOE 2009ct enclosure 6) (SER Vol. 3 pages 9-34 and 9-35)

- To address drift collapse, DOE developed a collapsed drift seepage table similar to the intact drift seepage lookup table. A tiered abstraction was used to account for the degree of drift degradation (SAR Section 2.3.3.4.1.1). (SER Vol. 3, page 9-35)

- DOE response to request for additional information regarding a maximum bound for seepage (DOE 2009cx enclosure 1) and DOE information on seepage as a percentage of percolation (DOE 2010ai Table 8) (SER Vol. 3 page 9-36)

- DOE response to request for additional information regarding the limited effect of reduction of the seepage threshold value on performance (DOE 2009ct enclosure 5) (SER Vol. 3 page 9-37)

- DOE's observations during a natural seepage event in the South Ramp of the Exploratory Studies Facility tunnel, which started in February 2005 and continued for several months, supported a seepage fraction significantly smaller than one. Results of a DOE simulation using its seepage model qualitatively reproduced the seepage fraction deduced from observations in the tunnel (SAR Section 2.3.3.4.3). – SER Vol. 3 page 9-38

- NRC independent analysis that the spacing of flowing fractures suggests the seepage fraction is likely less than one (Basagaoglu et al. 2007aa) (SER Vol. 3 page 9-38)

- DOE response to request for additional information regarding upscaled seepage and impact on spatial continuity and importance to performance (DOE 2009bo enclosure 2 (SER Vol. 3 page 9-39)

- NRC independent analysis and understanding for features and processes during the thermal period (NRC 2005aa; Green et al. 2008aa) (SER Vol. 3 pages 9-40 and 9-41)

- DOE response to request for additional information regarding drip shield integrity during the thermal period (DOE 2009bo enclosure 7) (SER Vol. 3 page 9-41)

**4) In-Drift Convection and Moisture Redistribution**

- DOE's drift scale model support provided by DOE's laboratory convection experiments and other experiments in the scientific literature using similar geometries (e.g., Kuehn and Goldstein, 1978aa).
- NRC contractor independent experiments and modeling studies support representation of heat transfer processes and engineering designs in DOE's convection models (Das et al., 2007aa; Green and Manepally 2006aa; Manepally et al., 2007ab) (SER Vol. 3 page 9-43)

- NRC independent analyses supporting DOE's assumption of using pure air in the convection model (Fedors et al., 2004aa) (SER Vol. 3 page 9-43)

- DOE's convection model to estimate effective thermal conductivity is acceptable because it follows a widely accepted technical approach used in engineering analyses (Kuehn and Goldstein, 1976aa, 1978aa) (SER Vol. 3 page 9-44)

- DOE response to request for additional information regarding the high likelihood that drifts will remain intact throughout the first 2,000 years – supports DOE approach that adds condensate to dripping flux (DOE 2009ct enclosure 7) (SER Vol. 3 page 9-46

- NRC contractor independent experiments and modeling of convection, vapor transport, and condensation in drift analogs (Das et al., 2007aa; Manepally et al., 2007ab) (SER Vol. 3 page 9-46)

- DOE response to request for additional information showing mean condensation rates are less than 1 percent of the mean seepage rates (DOE 2009ai Tables 6 and 7) (SER Vol. 3 page 9-46)

**6) Unsaturated flow below the repository affecting transport to the saturated zone**

- DOE description of flow patterns in the CHn (Calico Hills non-welded) unit that differ markedly between the northern and southern portions of the repository footprint (SAR Section 2.3.2.2.1.2) – SER Vol. 3 page 9-49

- NRC independent analyses regarding flow magnitudes and paths (Leslie et al., 2007aa; NRC 2005aa) – SER Vol. 3 page 9-49

- DOE response to request for additional information regarding the representation of flow through welded-tuff fractures and faults as fast pathways (DOE 2009an enclosure 6) (SER Vol. 3 page 9-50)

- NRC independent analyses and modeling studies supporting DOE's active fracture model and parameters (Basagaoglu et al., 2009aa) (SER Vol. 3 page 9-51)

- SAR Section 2.1.2.3.1 identifies travel times through the vitric CHn unit (high matrix permeability results in little or no fracture flow in this unit that exists below the southern portion of repository) are longer than units above and below and dominates the travel time for the entire sequence of units below the southern portion of the repository (SER Vol. 3 pages 9-51 and 9-52)

- NRC independent knowledge of site characteristics regarding estimates for areal extent and vertical variations of vitric and zeolitic units (Leslie et al., 2007aa Section 6.4; NRC 2005aa Section 5.1.3.6.4) (SER Vol. 3 page 9-53)
- DOE response to request for additional information regarding the rate of water movement controlling transport and the importance of moderately to strongly sorbing radionuclides (especially radionuclides with short half-lives) that pass through a matrix unit (DOE 2009an Enclosure 6) (SER Vol. 3 page 9-56)

- DOE response to request for additional information regarding the significance of non-sorbing and sorbing radionuclide in releases from the unsaturated zone (DOE 2009am Enclosure 1) (SER Vol. 3 pages 9-56 and 9-57)

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# 10.0 Unsaturated Zone Transport

Transport of radionuclides in the unsaturated zone are affected by the sorption on the mineral surfaces of the rock surfaces, matrix diffusion associated with fracture flow, and colloid-associated transport.

> *"In its Safety Analysis Report (SAR) Section 2.3.8 (DOE, 2008ab), DOE (i) described the features, events, and processes (FEPs) that DOE included to model the transport of radionuclides in groundwater in the unsaturated zone below the repository and (ii) provided the technical basis for DOE's implementation (or abstraction) of the unsaturated zone transport model in the Total System Performance Assessment (TSPA) model. The NRC staff's evaluation focuses on the following processes, detailed in subsequent sections, that DOE included in its SAR Section 2.3.8 as important for radionuclide transport in the unsaturated zone: (i) advection, because most of the radionuclide mass is carried through the unsaturated zone by water flowing downwards to the water table; (ii) sorption, because sorption in porous media in the southern half of the repository area has the largest overall effect on slowing radionuclide transport in the unsaturated zone; (iii) matrix diffusion in fractured rock, because matrix diffusion coupled with sorption slows radionuclide transport in the northern half of the repository area; (iv) colloid-associated transport, because radionuclides attached to colloids may travel relatively unimpeded through the unsaturated zone; and (v) radioactive decay and ingrowth, because these processes affect the quantities of radionuclides released from the unsaturated zone over time."* (SER Vol. 3, page 10-1)

## 10.1 Requirements Specific to Unsaturated Zone Transport

There are no requirements specific to unsaturated zone transport.

## 10.2 Performance Perspectives for Unsaturated Zone Transport

> *"DOE simulated the transport of radionuclides as (i) dissolved species and (ii) attached to mobile, colloid-sized particles. These two modes of transport are subject to various physical and chemical processes that affect radionuclide transport rates. DOE's conceptual model addresses how each of the transport-affecting processes influences the rate at which radionuclides travel through the unsaturated zone relative to the rate that water travels (SAR Section 2.3.8.2)."* (SER Vol. 3, page 10-3)

> *"In DOE's unsaturated zone transport model and abstraction, advection refers to the transport of radionuclides, as either dissolved or colloid-associated phases, by the bulk movement of water. DOE stated in SNL (2007bj, Section 6.1.2.1) that advection was probably the most important transport process in the unsaturated zone because the rate of water movement largely controls radionuclide travel times in the unsaturated zone. DOE coupled the advective transport of radionuclides with the bulk movement of water in fractures, in the rock matrix, and between fractures and matrix, using the groundwater flow rates and flow paths supplied by the site-scale unsaturated zone flow model, as detailed in SAR Section 2.3.8.5.2.1 and SNL (2008ag, Section 6.3.9.2). Because the unsaturated zone flow model predicts that water flows through the unsaturated zone at*

> *different rates in different rock units, the advective radionuclide transport rates vary correspondingly at different locations in the unsaturated zone. For example, in the fracture-dominated northern part of the repository area, DOE's unsaturated zone transport model predicts generally fast advective transport of radionuclides due to high modeled flow rates in fractures and fault zones. In the southern part of the repository area, advective transport of radionuclides in the unsaturated zone is slower due to low flow rates in the matrix-dominated flow system of the Calico Hills vitric tuff units (SAR Section 2.3.8.5.4)."* (SER Vol. 3, page 10-7)

The transport of those radionuclides (e.g., Pu and Am) that strongly sorb onto mineral surfaces in the matrix flow path are significantly delayed.

> *"In terms of the barrier capability of the lower unsaturated zone (SAR Section 2.1.2.3), DOE attributed a higher overall importance to sorption than to any other transport process, as identified in DOE (2009an, Enclosure 6)."* (SER Vol. 3, page 10-9)

Colloid-associated transport can circumvent sorption processes associated with dissolved radionuclides, however, DOE determined that this would not occur for a significant portion of the releases:

> *"DOE's colloid-associated transport model assumes that all irreversible colloids are generated within the EBS by the degradation of metals or waste form materials, and the only radionuclides associated with irreversible colloids are isotopes of plutonium and americium (SAR Section 2.3.7.12.3.2; SNL 2007bi, Section 6.3.1). On the basis of field evidence for fast colloid transport in groundwater (e.g., Kersting, et al., 1999aa), DOE designated a small fraction (less than 0.2 percent) of the irreversible colloid flux as a "fast fraction" that is transported from the EBS to the accessible environment without any retardation. The rest of the irreversible colloid flux is subject to several potential colloid retardation processes, including (i) fracture-related colloid attachment and detachment processes, as DOE detailed in SNL (2008an, Section 6.5.13); (ii) the direct release of irreversible colloids from the EBS into the low permeability rock matrix beneath the repository drifts, as described in DOE (2009am, Enclosure 9); and (iii) the advective transfer of irreversible colloids laterally from fracture flow paths into the rock matrix, subject to flow field conditions (i.e., matrix permeability large enough to accommodate the advective flux) and subject to colloid size exclusions at the fracture–matrix interface, as described in SAR Section 2.3.8.4.5.4 and SNL (2008ag, Sections 6.3.9.1 and 6.3.9.2). In SNL (2008ag, Section 6.3.9.1), and in SNL (2008an, Section 6.5.9), DOE also described a fourth retardation process, the matrix filtration (straining) of irreversible colloids at the interface between the matrix of one rock unit and the matrix of the underlying rock unit, resulting in the permanent immobilization of irreversible colloids in the unsaturated zone."* (SER Vol. 3, pages 10-19 and 10-20)

## 10.3 Key Review Topics for Unsaturated Zone Transport

The NRC staff's technical review focused on how DOE (i) developed a system description that incorporated site-specific transport-related geological, hydrological, and geochemical features of Yucca Mountain in the unsaturated zone transport abstraction, and (ii) established the technical basis for modeling the major risk-significant processes related to radionuclide transport in the unsaturated zone (e.g., advection, dispersion, matrix diffusion, and colloidal transport).

**1) Unsaturated zone flow paths below the repository**

- DOE response for request for additional information regarding representation of major faults in providing fast transport processes (DOE 2009am, Enclosure 2) - SER Vol. 3, page 10-3

- NRC prelicensing field observations and independent analyses of unsaturated zone transport processes (NRC 2005aa Section 5.1.3.7 and Leslie et al. 2007aa) – SER Vol. 3, page 10-4

- DOE response to request for additional information regarding features of the unsaturated zone beneath the repository contributed to barrier capability (DOE 2009am, Enclosure 1) - SER Vol. 3 page 10-4

- DOE stated that most radionuclides released from waste packages in seeping drifts are transferred by advection into fractures, and most radionuclides released from waste packages in nonseeping drifts are transferred by diffusion into the rock matrix (DOE 2009an, Enclosure 6) - SER Vol. 3 page 10-5

**2) Radionuclide Sorption**

- DOE identified release of radionuclides from the EBS into the rock matrix as a significant barrier mechanism because DOE models indicated that radionuclides travel more slowly in the rock matrix than they do in the fractures (SAR Section 2.3.8.5.4; SAR Figure 2.3.8-49; DOE, 2009am, Enclosure 9) - SER Vol. 3 page 10-5

- Sorption potentially can retard the transport of moderately or strongly sorbing radionuclides in the unsaturated zone for thousands of years or longer, contributing more significantly to unsaturated zone barrier capability than any other retardation process (DOE 2009an, Enclosure 6) – SER Vol. 3, page 10-9

- DOE developed ranges and statistical distributions of Kd (sorption coefficients) values for each radioelement and for each modeled rock unit from a combination of empirical data, process modeling, and professional judgment, as summarized in SAR Table 2.3.8-2; DOE detailed the Kd selection process in SNL (2007bj, Appendices A, B, I, and J and Addendum 1) and in DOE (2009am, Enclosure 3) – SER Vol. 3, page 10-9

- DOE approach to addressing this uncertainty was to use results from batch experiments for a range of particle sizes and to bias the minimum and maximum limits obtained for the Kd distributions toward lower (weaker sorption) values, as documented in DOE (2009am, Enclosure 3, Table 1.1.2-1) – SER Vol. 3, page 10-10

- NRC independent analyses regarding surface complexation models that provide similar insights to DOE's regarding radionuclide sorption behavior (e.g., Turner et al., 2002aa) – SER Vol. 3, page 10-11

- DOE based its sorption modeling on an empirical Kd modeling approach that is well established (e.g., Freeze and Cherry, 1979aa; Till and Meyer, 1983aa) and has been broadly used to describe radionuclide transport (e.g., Sheppard and Thibault, 1990aa; Chapman and McKinley, 1987aa) – SER Vol. 3, page 10-12

**3) Active Fracture Model and Matrix Diffusion**

- DOE field observations and transport simulations support the DOE statements in Section 6.4.1 of BSC (2006aa) that DOE has not overestimated the effectiveness of matrix diffusion in delaying the migration of radionuclides through the unsaturated zone in TSPA calculations – SER Vol. 3, page 10-16

- NRC evaluation of DOE's field and laboratory studies of fracture–matrix interactions in the unsaturated fractured rocks at Yucca Mountain and elsewhere, as detailed in NRC 2005aa, Section 5.1.3.7 and McMurry 2007aa – SER Vol. 3, page 10-17

- DOE addressed model uncertainty about the extent and importance of fracture–matrix interactions by varying the size and extent of the fracture–matrix interface area available for matrix diffusion over a large range of potential values, as detailed in SNL (2008an, Section 6.6.4), and by simulating the uncertain effect of spatially and temporally variable flow conditions on transport rates in unsaturated fractures, as provided in SNL (2008ag, Section 6.3.9.2) – SER Vol. 3, page 10-17

**4) Colloid-Associated Transport**

- DOE described an empirically determined colloid retardation factor to account for colloid attachment and detachment processes in fractures that can hinder colloid movement in fractures (BSC (2004bc, Section 6.4.3) – SER Vol. 3, page, 10-18

- DOE addressed data uncertainty for reversible colloids by selecting ranges of montmorillonite sorption coefficients that emphasized large Kd values (i.e., strong sorption onto colloids), so as not to underestimate the effectiveness of radionuclide attachment to colloid surfaces (DOE 2009am, Enclosure 14) – SER Vol. 3, page 10-18

- On the basis of field evidence for fast colloid transport in groundwater (e.g., Kersting, et al., 1999aa), DOE designated a small fraction (less than 0.2 percent) of the irreversible colloid flux as a "fast fraction" that is transported from the EBS to the accessible environment without any retardation – SER Vol. 3, page 10-20

- The conceptual and mathematical basis for the associated transport processes (e.g., retardation of colloids by attachment processes in fractures, reversible sorption of radionuclides onto colloids, colloid size exclusion processes at fracture–matrix interfaces, and unretarded colloidal transport) uses an approach that is consistent with existing models for contaminant transport in fractured rocks in the literature (e.g., Sudicky and Frind, 1982aa) – SER Vol. 3, page 10-21

**5) Radionuclide Decay and Ingrowth**

- DOE used a well-documented modeling approach with no significant uncertainties – SER Vol. 3, page 10-21
- DOE's model assumptions about the ingrowth-related transport behavior of decay chain radionuclides in irreversible colloids are consistent with DOE's model assumptions about the sorption behavior of the same radionuclides where

they are associated with reversible colloids in DOE's model – SER Vol. 3, page 10-21

## 10.4 References Specific to Unsaturated Zone Transport


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# 11.0 Flow Paths in the Saturated Zone

The saturated zone flow path extends from the repository to the 18-km [11.2-mi] compliance boundary (SER Vol. 3, page 11-13). A portion of this long flow path is in the alluvium where groundwater flow is slow relative to the portion of the flow path that is in fracture rock units. Additionally, radionuclide sorption can be significant in the alluvium unit.

> *"The NRC staff reviewed information provided in the DOE's Safety Analysis Report (SAR) included with the license application submitted on June 3, 2008 (DOE, 2008ab) and subsequent update of February 19, 2009 (DOE, 2009av), and information provided in response to requests for additional information (RAIs) (DOE, 2009an,bc).*
>
> *Features and processes of groundwater flow in the saturated zone are included in DOE's performance assessment evaluation for the proposed geologic repository at Yucca Mountain, Nevada. The performance assessment analysis described in SAR Section 2.4.2.3.2.1 includes the flow of water (i) starting from precipitation falling on Yucca Mountain, (ii) in the unsaturated zone above and below the repository, and (iii) in the saturated zone through the controlled environment to the accessible environment. This groundwater is the principal means by which radionuclides released from the repository could be transported to the accessible environment (SAR Section 2.1). Exposure to extracted groundwater is one of the risk-significant pathways to the reasonably maximally exposed individual (RMEI)."* (SER Vol. 3, page 11-1)

## 11.1 Requirements Specific to Flow Paths in the Saturated Zone

There are no specific requirements for the flow paths in the saturated zone.

## 11.2 Performance Perspectives for Flow Paths in the Saturated Zone

Sorption of radionuclides along the alluvial flow path portion of the saturated zone flow path can significantly delay the transport of those radionuclides (e.g., Pu and Am) that strongly sorb onto mineral surfaces. Thus, accounting for the portion of the saturated zone flow path that is made-up of the alluvial deposits is risk-significant to the performance assessment as compared with the portion of the saturated zone flow path that is in fractured volcanic tuffs where sorption has less effect.

> *"DOE identified the saturated zone as a feature important to the capability of the lower natural barrier (SAR Section 2.1.1.3). Specifically, DOE indicated in DOE (2009an, Table 2.1-1 Expanded) that a combination of slow advective flow, long transport distance, and geochemical retardation of radionuclides in the saturated zone can substantially reduce the rate of radionuclide movement to the RMEI location. Saturated zone groundwater flow, as described in SAR Section 2.3.9.1, includes the features, events, and processes (FEPs) that affect the movement of groundwater in the saturated zone to the accessible environment and their implementation (or abstraction) in the Total System Performance Assessment (TSPA)." (SER Vol. 3, page 11-1)*

*"The one-dimensional saturated zone transport abstraction model, which provides the transport simulation capability for radionuclide daughter products resulting from decay and ingrowth, uses a simplistic one-dimensional representation of the three-dimensional saturated zone flows. The one-dimensional saturated zone transport abstraction model consists of three pipe segments. The first pipe segment is 5 km [3.1 mi] long. The lengths of the second and third pipe segments are estimated from particle tracking results of the three-dimensional saturated zone flow and transport abstraction model. The variable lengths account for uncertainty in the location of the volcanic/alluvial aquifer contact."* (SER Vol. 3, page 11-6)

## 11.3 Key Review Topics for Flow Paths in the Saturated Zone

The NRC staff's technical evaluation focused on the applicant's delineated flow path directions and distances and the applicant's estimates of specific discharge for both present and future conditions as presented SAR Section 2.3.9 and the supporting documents.

**1) Models relevant to flow paths in the saturated zone (DOE used multiple models at different scales to describe and quantify portions of the saturated zone groundwater flow system in the vicinity of the Yucca Mountain site)**

- Death Valley groundwater system (regional scale) reflects the arid climatic conditions and complex geology of the Basin and Range flow system with groundwater flowing generally from north to south (SAR Section 2.3.9.2.1) – SER Vol. 3, page 11-4

- Site-scale hydrogeologic framework model covering the spatial distribution of hydrogeologic units in the Yucca Mountain area to a depth of about 6 km [3.7 mi] including 10 distinct hydrogeologic features (SNL 2007an,ax) – SER Vol. 3, page 11-5

- Site scale model provided the TSPA model with 200 radionuclide unit mass breakthrough curves at the compliance boundary for 4 source subregions and 12 radionuclide groups, resulting in 9,600 breakthrough curves (SAR Figure 2.3.9-16) – SER Vol. 3, page 11-6

- One-dimensional saturated zone transport model to represent the three-dimensional saturated zone flow including the average discharge along each pipe or segment (BSC 2005ak) – SER Vol. 3, page 11-6

**2) Data supporting flow paths in the saturated zone**

- Hydraulic and tracer tests (cross-hole tests) at the C-Wells Complex, consisting of boreholes UE-25 c#1, UE-25 c#2, and UE-25 c#3 (SAR Figure 2.3.9-7) including information on stratigraphy, lithology, matrix porosity, fracture density and the major flowing intervals (SNL 2007ba and SAR Section 2.3.9.2.4.2)– SER Vol. 3, pages 11-7 and 11-8
- Water level-level calibration targets represent steady-state values and reflect current uses wherever pumping takes place (SNL 2007ax) – SER Vol. 3 page 11-8

- Observational information used to calibrate site-scale saturated zone flow model for water flow between the lower and upper aquifers (SNL 2007ax and DOE 2009bc Enclosure 3) – SER Vol. 3, page 11-9

- Although NRC identified some limitations in DOE's Bayesian statistical procedure for treatment of data uncertainty (DOE 2009bc Enclosures 1 and 2), the NRC determined that the limitations would not significantly affect dose estimated in the performance assessment – SER Vol. 3, pages 11-12 and 13

- NRC independent estimates for horizontal hydraulic conductivity anisotropy based on site specific data for volcanic tuffs (Ferrill et al., 1999aa) and independent analysis of Fortymile Wash alluvium as a gravel-dominated 'fast' flow path (Sun et al., 2008aa)

- NRC independent evaluation of well drilling records from the Nye County – Early Warning Drilling Program with respect to uncertainties associated with the actual geometry of the volcanic and alluvium contact (Bertetti et al. 2001aa, Winterle and Farrell 2002aa and Sun et al., 2008aa) – SER Vol. 3, pages 11-13 and 11-14

**3) Model Uncertainties and Alternative Models**

- Regarding the permeability in the high-gradient regions: DOE concluded that, although the cause of the high gradient is not entirely certain, it is nevertheless important to represent this feature in the model for present-day conditions because removal of this feature would result in a significant increase in the specific discharge downgradient from the repository – SER Vol. 3, page 11-16

- Regarding a rising water table: NRC independent analysis by Winterle (2005aa) indicates an elevated water table would not significantly affect flow paths from beneath the proposed repository area – SER Vol. 3, page 11-17

- Regarding the potential for a fault dominated flow system: NRC staff acknowledged that numerous realizations in the performance assessment produce saturated zone transport times for nonsorbing solutes on the order of 10 to 100 years for the glacial-transition climate state (SAR Section 2.3.9.3.4.1 and Figure 2.3.9-16) and concluded that these realizations with rapid transport times reasonably represent the potential for focused high-permeability flow paths – SER Vol. 3, pages 11-17 and 11-18

- Regarding analyses of Freifeld et al. (2006aa) of Nye County well 24PB suggesting significantly larger specific discharges of 5 - 310 m/yr: (1) DOE provided that the high flow rate was observed in a relatively narrow interval of the borehole and that upscaling this estimate using an assumed median flow interval spacing of 25.8 m [84.6 ft] (from the parameter uncertainty distribution) reduces the estimated specific discharge to a range of 0.07 – 4.1 m/yr; and (2) NRC staff found "the results reported in Freifeld, et al. (2006aa) are not conclusive regarding horizontal specific discharge at the scale of interest to the model abstraction, but generally support the concept of widely spaced, flowing intervals in the volcanic tuff units" – SER Vol. 3, page 11-19

## 11.4 References Specific to Flow Paths in the Saturated Zone

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# 12.0 Radionuclide Transport in the Saturated Zone

Transport of radionuclides in the saturated zone is impacted primarily by sorption in the alluvium unit that has relatively slow groundwater flow rates relative to the other fractured volcanic units of the saturated zone.

> *"Radionuclide transport in the saturated zone, as described in SAR Section 2.3.9, includes the features, events, and processes (FEPs) that affect the movement of radionuclides from where they enter the saturated zone below the repository to the accessible environment boundary approximately 18 km [11.18 mi] south of the repository and their implementation (or abstraction) in the TSPA."* (SER Vol. 3, page 12-1)

## 12.1 Requirements Specific to Radionuclide Transport in the Saturated Zone

There are no requirements specific to radionuclide transport in the saturated zone.

## 12.2 Performance Perspectives for Radionuclide Transport in the Saturated Zone

The volcanic rock and alluvium units have very different properties that results in sorption in the alluvium unit being the most significant to performance, although matrix diffusion in the volcanic rock units will also result in some delay in the transport of radionuclides.

> *"DOE related Yucca Mountain site characteristics to a conceptual model of the saturated zone extending from beneath the repository to the accessible environment boundary in which the flow of water would transport radionuclides through two primary geological units (fractured volcanic tuff and alluvium) and through major faults. In DOE's model, the disparate geological properties of the fractured volcanic rock and the alluvium are expected to have very different effects on water flow and radionuclide transport.*
>
> *
> *
> *
>
> *On the basis of field and modeling studies, DOE determined that for modeling purposes, groundwater flow and migration of radionuclides in the saturated zone would begin in fractured volcanic rock beneath the repository and would extend southeasterly toward Fortymile Wash before turning in a southerly direction beneath the wash, continuing from there towards the accessible environment boundary located approximately 18 km [11.18 mi] south of the repository. The subsurface contact between volcanic rock and the alluvium along this path occurs approximately 10 km [6.21 mi] south of the repository, at which point*

*the water and radionuclides are expected to pass out of the volcanic rock and into the porous alluvium."* (SER Vol. 3, page 12-4)

*"DOE identified sorption as an important process contributing to the barrier capability of the saturated zone (SAR Section 2.3.9). In particular, DOE model results indicate that sorption within the alluvium effectively delays the transport of moderately and strongly sorbing radionuclides for thousands of years or longer (SAR Sections 2.3.9 and 2.1.2.3.6). DOE estimated that sorption of dissolved thorium, americium, and protactinium is so effective in the saturated zone that, upon entering the saturated zone, these radionuclides cannot traverse it to reach the accessible environment within the regulatory period of 1 million years. For these radionuclides to be present at the accessible environment boundary within the million-year timeframe, DOE determined that they must either be transported through the saturated zone as colloids or be ingrown as the decay products of mobile parents."* (SER Vol. 3, page 12-12)

## 12.3 Key Review Topics for Radionuclide Transport in the Saturated Zone

The NRC staff's technical evaluation focused on the applicant's incorporation of site-specific geological, hydrological, and geochemical features of Yucca Mountain in the saturated zone radionuclide transport model and the technical basis for the major processes considered by DOE (advection and dispersion, sorption, matrix diffusion, colloid-associated transport, and radionuclide decay and ingrowth) as presented in SAR Section 2.3.9.

**1) Alluvium Transport Path**

- The specific location of the contact between volcanic rock and alluvium along the flow path is a key geologic data uncertainty in DOE's transport abstraction (BSC, 2005ak) – SER Vol. 3, page 12-4

- In SNL (2008ag, Section 6.3.10) DOE presented sensitivity analyses and single-realization analyses of TSPA simulations to demonstrate how the saturated zone transport abstraction integrated the specific transport-related processes with the natural features of the saturated zone to slow the migration of radionuclides through the saturated zone - SER Vol. 3, page 12-5

- DOE addressed the effect of wetter climates on radionuclide transport by using specific discharge multipliers to simply increase the radionuclide flux for each future climate state, so that a larger mass reaches the accessible environment boundary. DOE compared the simplified modeling approach with a more detailed consideration of the effect of changes in water table elevations and flow rates in the saturated zone by using a three-dimensional site-scale transport model to generate particle tracks for the wetter climate states (SNL, 2007ba, Appendix E; DOE, 2009de). DOE stated the particle tracking results demonstrated that exclusion of these effects in the saturated zone transport model for TSPA did not result in an underestimation of dose, because the path lengths and travel times of radionuclides increased relative to the simplified use of specific discharge multipliers for radionuclide flux that DOE used in the performance assessment (SNL, 2007ba, Appendix E). – SER Vol. 3, page 12-5

- NRC staff's understanding of the Yucca Mountain natural system, obtained from prelicensing field observations and independent analyses of saturated zone transport processes, as identified in NRC (2005aa) and Leslie, et al. (2007aa) – SER Vol. 3, page 12-6

**2) Saturated zone transport processes (advection and sorption, and matrix diffusion)**

- Values for the flowing interval porosity for the volcanic units were estimated using various conservative tracers and reactive tracers in C-Wells Complex testing (SNL, 2007aw) – SER Vol. 3, page 12-10

- Although DOE's conceptual model does not explicitly account for all possible flow paths within the alluvium, the NRC staff considered the effective porosity approach to be an acceptable method for incorporating preferential pathways and travel time in the alluvium because it was compatible with observed site characteristics, such as the occurrence of gravel paleochannels and lenses of clay (Bertetti and Prikryl, 2003aa; Nye County NWRPO, 2003aa; Ressler, et al., 2000aa) – SER Vol. 3, page 12-11
- DOE cited laboratory and field-scale transport experiments to support its conceptual model of colloid retardation in fractures (BSC, 2005ak; SNL, 2007aw) – SER Vol. 3, page 12-12

- DOE measured sorption data from batch and column experiments that used site-specific samples of crushed tuff and alluvium, and the experiments used water chemistry based on water samples from wells in the saturated volcanic tuff (UE-25 and J-13), carbonate aquifer (UE-25 p#1), and alluvium (various EWDP wells) (SNL, 2007ba, Appendices A and G) – SER Vol. 3, page 12-13

- General DOE approach to address sources of uncertainty from mineral surface area and particle size was to use batch experiments for a range of particle sizes and to bias the minimum and maximum limits for the Kd distributions toward lower (weaker sorption) values (DOE 2009am, Table 1.1.2-1) – SER Vol. 3, page 12-13

- DOE's TSPA calculations sampled Kd values from the specified ranges to account for experimental uncertainty and variability in geologic conditions, including water chemistry and rock type, as shown in SAR Table 2.3.9-4; BSC (2005ak); SNL (2007ba, Appendices A, C, G, and J); and DOE (2009am, Enclosure 3) – SER Vol. 3, page 12-13

- NRC independent analyses of the surface area of site-specific materials and surface area effects on sorption (Bertetti, et al., 2004aa; Bertetti, et al., 2011aa) – SER Vol. 3, page 12-14

- The chemistry of alluvial aquifer waters used in alluvium sorption experiments is representative of conditions in the alluvium (McMurry and Bertetti, 2005aa) – SER Vol. 3, pages 12-14 and 12-17

- The Kd approach developed from empirical data, as implemented by DOE, is simplistic but well established (e.g., Freeze and Cherry, 1979aa; Till and Meyer, 1983aa), and it has been broadly accepted in modeling studies for decades as a method to describe radionuclide transport (e.g., Sheppard and Thibault, 1990aa) – SER Vol. 3, page 12-15

- The range of groundwater compositions used by DOE to establish radionuclide transport parameters encompasses the temporal variances that have been documented during Yucca Mountain site characterization activities (Turner and Pabalan, 1999aa) – SER Vol. 3, page 12-16

- DOE's sorption/desorption experiments (SNL 2007ba, Appendix J) – SER Vol. 3, page 12-16

- DOE's response to an RAI concerning biasing of Kd values in TSPA to lower values (DOE, 2009df) led to the consideration that concentrations of some decay chain daughters could be underestimated if secular equilibrium is assumed; however, the NRC staff's independent analyses confirmed the impact was not significant to performance (Bradbury, 2010aa) – SER Vol. 3, page 12-18

**3) Colloid associated transport and radionuclide decay and ingrowth**

- Data from field experiments indicate some colloids travel with little or no retardation (Kersting, et al.,1999aa; SNL, 2007aw) and thus DOE designated a small fraction (less than 0.2 percent) of the irreversible colloid flux as a completely unretarded "fast fraction" – SER Vol. 3, page 12-20

- DOE provided model results that are consistent with cross-hole field tests using microspheres showing decreased retardation of colloid-associated radionuclides relative to dissolved constituents. The modeling results and field-test results are consistent with the Kc factor approach used to represent colloid-associated transport (BSC 2004bc) – SER Vol. 3, page 12-21

- DOE selected a set of radioelements that are most strongly sorbed to model colloidal-facilitated transport - the radioelements that are the most strongly sorbed to the colloids are those that contribute the most to dose (SNL 2008ag) – SER Vol. 3, page 12-21

- DOE response to the NRC request for additional information regarding differences in sorption characteristics between parent and daughter radionuclides (e.g., disequilibria between parent and daughter may develop along a transport path if a long-lived parent is more strongly sorbed than its decay products) identified that the dose could increase from a value of 2 mrem [0.02 mSv] to a value of 2.4 mrem [0.024 mSv] due to the sorption differences . (DOE 2009df) – SER Vol. 3, pages 12-23 and 12-24

- NRC independent analyses regarding DOE's conclusion that deviations from secular equilibrium would not significantly affect TSPA results and differences in sorption characteristics between parent and daughter radionuclides (Bradbury 2010aa) – SER Vol. 3, pages 12-24 and 12-25

- Conditions favoring excess Po-210 have not been observed along the potential flow path in the saturated-zone alluvium south of the controlled boundary (SNL, 2007ax; SNL, 2007ba; BSC, 2004bc; Bertetti, et al., 2004aa) – SER Vol. 3, page 12-25

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# 13.0 Igneous Disruption of Waste Packages

The SER section on Igneous Disruption of Waste Packages evaluated DOE's model for the potential consequences of disruptive igneous activity at Yucca Mountain if

> *"basaltic magma rising through the Earth's crust enters repository drifts [DOE's igneous intrusion modeling case, Safety Analysis Report (SAR) Section 2.3.11.3 (DOE, 2009av)] or enters a drift and later erupts to the surface through one or more conduits (DOE's volcanic eruption modeling case, SAR Section 2.3.11.4). The proposed Yucca Mountain repository site lies in a region that has experienced sporadic volcanic events in the past few million years. DOE previously determined the probability of future igneous activity at the site to exceed 1 × 10−8 per year (SAR Section 2.2.2.2; CRWMS M&O, 1996aa; evaluated in SER Section 2.2.1.2.2). DOE therefore included igneous activity as one of three scenario classes in its performance assessment."* (SER Vol. 3, page 13-1)

## 13.1 Requirements Specific to Igneous Disruption of Waste Packages

> *"This model abstraction involves igneous activity, i.e. intrusive or volcanic disruption of waste packages. The requirements in 10 CFR 63.342(c)(1) pertain to the effects of seismic and igneous activity on the repository performance, subject to the probability limits in 10 CFR 63.342(a) and 63.342(b). Specific constraints on the seismic and igneous activity analyses are in 10 CFR 63.342(c)(1)(i) and (ii), respectively."* (SER Vol. 3, Page 13-3)

In particular, 10 CFR 63.342(c)(1)(ii) states:

> *"The igneous activity analysis may be limited to the effects of a volcanic event directly intersecting the repository. The igneous event may be limited to that causing damage to the waste packages directly, resulting in releases of radionuclides to the biosphere, atmosphere, or ground water."*

## 13.2 Performance Perspectives for Igneous Disruption of Waste Packages

The igneous intrusion scenario is assumed to disrupt all the waste package, therefore, this scenario is one of the major contributors to the overall dose despite the likelihood for such an event is very small (e.g., much less than 1 chance in 1,000,000 per year).

> *"To evaluate the potential effect of future igneous activity on dose to the RMEI, DOE adopted a conceptual model in which rising basalt magma entering a repository drift (or drifts) could cause release of radionuclides via two pathways (SAR Section 2.3.11.1). The first pathway is intrusive igneous events, where magma rising toward the surface as a dike, or set of dikes, enters the drifts but stays beneath the surface.*
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>
> *In the igneous intrusive scenario, DOE assumed that all drifts in the repository are intersected by the dike(s), magma fills all drifts, and all waste packages in the repository are damaged*

*but remain in the drifts. No waste is released directly into the accessible environment in an intrusive-only igneous event, but radionuclides are released to the accessible environment through subsequent groundwater transport. DOE models this transport to occur through the same pathways represented in the nominal, seismic, and early failure scenario classes, which are evaluated in SER sections on unsaturated zone flow and transport (SER Sections 2.2.1.3.6, 2.2.1.3.7, 2.2.1.3.8, and 2.2.1.3.9).*

*The second pathway is an extrusive, or volcanic, igneous event. DOE considered a scenario where magma continues to rise to the surface as a dike after intersecting repository drifts and, on the basis of the behavior of basaltic eruptions in general, that surface activity along the resulting initial fissure (the surface expression of a dike) would rapidly localize, or focus, to a single, or few, points of magma effusion (SNL, 2007ae; SAR Section 2.3.11.4.1). A volcanic conduit wider than the dike would be expected to develop at that focus somewhere along the dike by excavation from the surface (vent) downwards. This conduit can potentially intersect a drift(s) or develop in the area between the drifts. Magma flow up a drift-intersecting conduit would entrain waste from disrupted packages, thereby providing a direct pathway for waste material to be released to the accessible surface environment during a volcanic eruption."* (SER Vol. 3, pages 13-4 ND 13.5)

*"As stated in the Introduction (SER Section 2.2.1.3.10.1) of this section, while the probability of an igneous event is low, the consequences could be high. The igneous intrusion modeling case would constitute most of the calculated dose to the RMEI for the first 1,000 years following permanent closure of the repository, as shown in SAR Figure 2.4-18(a), and is approximately half the DOE calculated dose for the seismic ground motion modeling case in the ensuing 9,000 years.*

*In SAR Section 2.4.2.2.1.2.3, DOE provided its estimate of probability-weighted consequences of igneous activity (intrusive and extrusive) using the probability distribution from its expert elicitation for a Probabilistic Volcanic Hazard Assessment (PVHA). DOE identified that the probability-weighted igneous mean intrusive dose is estimated to be less than 0.001 mSv/yr [0.1 mrem/yr] for the 10,000-year period and the median dose less than 0.005 mSv/yr [0.5 mrem/yr] for the post-10,000-year time period (SAR Section 2.4.2.2.1.2.3.1). DOE estimates for the probability-weighted igneous extrusive (volcanic eruptive) mean dose alone are on the order of 10−6 mSv/yr [0.0001 mrem/yr] for the 10,000-year period and the median dose is less than $6 \times 10^{-7}$ mSv/yr [$6 \times 10^{-5}$ mrem/yr] for the post-10,000-year time period (SAR Section 2.4.2.2.1.2.3.2). The NRC staff notes that the difference in magnitude for the dose consequences between the two igneous scenarios (intrusive and extrusive) predominantly results from the different number of waste package failures estimated to occur for each scenario, which causes the dose from the extrusive case to be several orders of magnitude below the intrusive case (SAR Section 2.2.1.4.1; evaluated in SER Section 2.2.1.3.10.3.3."* (SER Vol. 3, page 13-6)

## 13.3 Key Review Topics for Igneous Disruption of Waste Packages

The NRC staff reviewed both intrusive and extrusive events.

*"The NRC staff's review is based on information presented in SAR Section 2.3.11 and relevant analysis and model reports (AMRs), material in other publicly available DOE and NRC reports, and relevant information published in peer-reviewed literature. The applicant also described and evaluated background information used to assess the likelihood and*

*type of future igneous activity in the Yucca Mountain region in SAR Volume 1, General Information, and Volume 2, Section 1.1.2. That material is reviewed in SER Section 2.1.1.1.3.6 as part of the NRC staff's evaluation of the applicant's site characterization."* (SER Vol. 3, page 13-4)

**1) Effects of Igneous Intrusion on Performance of Natural Barriers**

- DOE assumed igneous intrusion degraded the drifts and removed the groundwater seepage barrier (i.e., seepage set equal to percolation) and DOE's sensitivity analyses indicate potential alteration of hydrologic properties near repository drifts have a small effect on performance (SNL 2008ac -FEP 1.2.04.02.0A) – SER Vol. 3, page 13-6

- Dikes and sills that can potentially modify saturated zone flow represent a small area relative to the area of the saturated zone flow (SAR Section 2.3.11.3.2 and SNL 2007ag) - SER Vol. 3, page 13-7

**2) Behavior of Intruding Magma in Drifts and Effects on the Engineered Barrier System**

- Basaltic magmas expected to have relatively high dissolved water content that could cause the magma to flow more rapidly (SNL, 2007ae, Nicholis and Rutherford 2004aa) – SER Vol. 3, pages 13-7 and 13-8

- Drifts are assumed to fill quickly and disrupt all waste packages based on SAR Sections 2.3.11.2.1.2 and 2.3.11.3; SNL, 2007ag; Dartevelle and Valentine, 2005aa, 2009aa; and NRC independent analyses (Woods, et al., 2002aa; Lejeune, et al., 2009aa) – SER Vol. 3, page 13-8

- All waste package and drip shield barrier capabilities are removed in models for igneous intrusive events, resulting in unprotected waste forms that are immediately available for hydrologic transport once the intrusive basalt rock is cool enough for water to contact waste (SAR Section 2.3.11.3.2.4) – SER Vol. 3, page 13-8

- For an igneous intrusion event occurring after about 1,000 years into the postclosure period, DOE concluded that the repository drift walls would attain a temperature of 100 °C [212 °F] about 100 years after the intrusive event occurs, as in SNL 2008ag (Figure 2.3.5-33) – SER Vol. 3, page 13-10

- DOE concluded that the modeled changes in groundwater chemistry after contact with a basalt-filled drift would be negligible based on the relatively small volume of intruded basalt in comparison with the volume of host rock (SAR Section 2.3.11.3.3.9) – SER Vol. 3, page 13-12

**3) DOE volcanic eruption modeling scenario**

- In DOE's model, magma flow to the surface in the dike usually localizes to a single, or a few, points over a period of hours to a few days, as observed at past basaltic eruptions - such behavior was seen in analogous historic events [e.g., the 1943–1952 eruption of Paricutín in Mexico, the 1973 Heimaey eruption in Iceland, and the 1975 Tolbachik eruption in Kamchatka (Pioli, et al., 2008aa; Thorarinsson, et al., 1973aa; Doubik and Hill, 1999aa)]; and DOE studies of igneous products exposed in the rock record also inferred a similar progression for some prehistoric basaltic eruptions (e.g., SAR Section 2.3.11.4; SNL, 2007ae; Valentine, et al., 2006aa; Keating, et al., 2008aa) - – SER Vol. 3, page 13-13

- The DOE model for conduit formation is based on observations at basaltic volcanoes and is supported by calculations constrained by information obtained from studies of analogous eroded volcanoes (SNL, 2007ae) – SER Vol. 3, page 13-14

- NRC independent analyses of the characteristics of basaltic volcanism at the Yucca Mountain region and elsewhere that inform the NRC staff understanding regarding the acceptability of the number and spacing of conduit development along a dike (Hill and Conner, 2000aa; Doubik and Hill, 1999aa) – SER Vol. 3, page 13-15

- In DOE's model, uncertainty in conduit size is bounded by a size distribution based on observed host-rock fragments in violent-Strombolian deposits at the Lathrop Wells volcano (Doubik and Hill, 1999aa; SNL, 2007ae, Section 6.4 and Appendix C) and on field studies at analogous sites, which DOE interpreted as suggesting that the diameter is largest at the surface and decreases with depth – SER Vol. 3, page 13-16

- The DOE performance assessment calculates that the expected annual dose from the igneous extrusive volcanic modeling case alone is approximately 0.1 percent of the dose calculated for the igneous intrusive scenario (SNL, 2007ag) – SER Vol. 3, page 13-14

## 13.4 References Specific to Igneous Disruption of Waste Packages


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## 14.0 Concentration of Radionuclides in Groundwater

DOE's Safety Analysis Report (SAR) (DOE, 2008ab) provided information on the concentration of radionuclides in groundwater extracted by pumping and used in the annual water demand of the reasonably maximally exposed individual (RMEI). The relevant sections are Section 2.3.9, which includes discussions of saturated zone radionuclide transport; and Section 2.4.4, which includes the applicant's analysis of repository performance, which states the proposed repository would meet the standards for the protection of groundwater.

### 14.1 Requirements Specific to Concentration of Radionuclides in Groundwater

> *"The regulatory requirement for the annual well water demand to be used for evaluating the concentration of radionuclides in the groundwater is specified in 10 CFR 63.312(c), which states that the RMEI uses well water with average concentrations of radionuclides based on an annual water demand of 3,000 acre-ft [3.7 × $10^9$ L]."* (SER Vol. 3, Page 14-1)

### 14.2 Performance Perspectives for Concentration of Radionuclides in Groundwater

> *"In SAR Section 2.4.4, the applicant stated that it assumed that all radionuclides transported by groundwater from the Yucca Mountain disposal system in a given year are captured in the annual water demand of 3,000 acre-ft [3.7 × $10^9$ L]. The applicant determined the annual mean concentrations of transported radionuclides in the saturated-zone groundwater by dividing the annual mass flux of radionuclides reaching the accessible environment boundary by the annual water demand (SAR Section 2.4.4.1.1.1). As presented by the applicant in SAR Section 2.3.9, this annual mass flux includes both those radionuclides explicitly transported in the Total System Performance Assessment model and those calculated assuming secular equilibrium in long-lived decay chains."* (SER Vol. 3, pages 14-1)

### 14.3 Key Review Topics for Concentration of Radionuclides in Groundwater

Assuming all releases are captured by the annual water demand simplifies the review (i.e., the concentration cannot be larger).

*"YMRP Section 2.2.1.3.12 states that if the applicant assumes that all radionuclides that reach the RMEI in a given year are included in the pumping wells in the annual water demand of 3,000 acre-ft [3.7 × $10^9$ L], then the NRC staff should conduct a simplified review focusing on the bounding assumptions. In SAR Section 2.4.4, the applicant stated that it assumed that all radionuclides transported by groundwater from the Yucca Mountain disposal system in a given year are captured in the annual water demand of 3,000 acre-ft [3.7 × $10^9$ L]. Therefore, the NRC staff followed the simplified review approach, consistent with YMRP Section 2.2.1.3.12. The NRC staff verified that the applicant determined the annual mean concentrations of transported radionuclides in the saturated-zone groundwater by dividing the annual mass fluxes of radionuclides reaching the accessible environment boundary by the annual water demand (SAR Section 2.4.4.1.1.1). The NRC staff evaluation of the radionuclide mass flux is provided in SER Section 2.2.1.3.9. The applicant's saturated zone transport abstraction model (SAR Section 2.3.9) tracks transport of a set of contaminant radionuclides and assumes that long-lived, decay-chain daughter radionuclides are in secular equilibrium with their parents at the accessible environment boundary. As discussed in SER Section 2.2.1.3.9, this assumption may not be reasonable for cases where a long-lived parent radionuclide is more strongly sorbed than its decay products. In its response to the NRC staff's request for additional information, the applicant evaluated this effect and showed that for the conditions expected in the saturated zone transport path, the magnitude of the predicted excess daughter activity is not significant for performance (DOE, 2009df). The NRC staff concludes in SER Section 2.2.1.3.9 that, including the uncertainty from possible excess activity of decay-chain daughter radionuclides, the applicant's representation of the annual mass fluxes of radionuclides reaching the accessible environment boundary is acceptable."* (SER Vol. 3, pages 14-1 and 14-2)

## 14.4 References Specific to the Concentration of Radionuclides in Groundwater

DOE. 2009df. "Yucca Mountain—Response to Request for Additional Information Regarding License Application (Safety Analysis Report Section 2.3.9), Safety Evaluation Report Vol. 3, Chapter 2.2.1.3.9, Set 1." Letter (November 16) J.R. Williams to J.H. Sulima (NRC). ML093210213. Washington, DC: DOE, Office of Technical Management.

# 15.0 Airborne Transport and Redistribution of Radionuclides

The eruption through the repository had the potential to damage waste packages within the conduit with the entrainment of radionuclides in the magma and redistributing the radionuclides within the volcanic ash on the surface of the earth. The redistribution of the radionuclides within the soil results in a potential exposure pathway for humans.

> *"Safety Evaluation Report (SER) Section 2.2.1.3.13 evaluates the U.S. Department of Energy's (DOE, or the applicant) information on airborne transport and deposition of radionuclides expelled by a potential future volcanic eruption following igneous disruption of waste packages. It also evaluates DOE information on the redistribution of those radionuclides in soil. This evaluation of DOE's performance assessment for the volcanic eruption modeling case is a sequel to the evaluation of possible igneous disruption of the proposed repository (DOE's igneous intrusion modeling case; see SER Section 2.2.1.3.10). This SER Section also evaluates redistribution of radionuclides in soil in the accessible environment, which in the DOE model arrives in the accessible environment via groundwater transport. The U.S. Nuclear Regulatory Commission (NRC) staff's evaluation is based on information in the DOE Safety Analysis Report (SAR) (DOE, 2009av), as supplemented by DOE responses (DOE, 2009bk–bm) to the NRC staff's requests for additional information (RAIs).*" (SER Vol. 3, page 15-1)

## 15.1 Requirements Specific to Airborne Transport and Redistribution of Radionuclides

> *"This model abstraction of airborne transport and redistribution of radionuclides involves igneous activity. Thus, 10 CFR 63.342(c)(1) also applies to this abstraction, as this regulation requires that DOE assess the effects of seismic and igneous activity on the repository performance, subject to the probability limits in 63.342(a) and 63.342(b). Specific constraints on the analysis required for seismic and igneous activity are set forth in 10 CFR 63.342(c)(1)(i) and (ii), respectively."* (SER Vol. 3, Page 15-3)

In particular, 10 CFR 63.342(c)(1)(ii) states:

> The igneous activity analysis may be limited to the effects of a volcanic event directly intersecting the repository. The igneous event may be limited to that causing damage to the waste packages directly, causing releases of radionuclides to the biosphere, atmosphere, or ground water.

## 15.2 Performance Perspectives for Airborne Transport and Redistribution of Radionuclides

The risk from an eruptive volcanic event makes a small contribution to the overall risk primarily due to the low likelihood for the volcanic scenario (i.e., much less than 1 chance in 1,000,000 per year of occurring) and the limited number of waste packages entrained in an eruptive event.

*"The volcanic ash exposure scenario and groundwater exposure scenario provide different contributions to repository performance in the DOE assessment. The NRC staff finds acceptable the applicant's assessment that the volcanic ash exposure scenario following an eruption does not significantly influence repository performance, because DOE shows that its mean dose contribution is more than a factor of 1,000 smaller than the overall peak dose within the initial 10,000 years and more than a factor of 10,000 smaller than the overall peak dose after 10,000 years (SAR Figure 2.4-18). Further, DOE's dose exposure assessment is consistent with the NRC staff's independent analyses (see SER Section 2.2.1.4.1.3.3.2). The remaining DOE modeling cases depicted in SAR Figure 2.4-18 constitute the groundwater exposure scenario. The groundwater exposure scenario dominates the overall peak dose within 10,000 years and after 10,000 years (SAR Figure 2.4-18). This risk information suggests that the NRC staff should focus on the surface soil submodel in the groundwater exposure scenario and conduct a simplified review of the volcanic ash exposure focusing on the bounding assumptions."* (SER Vol. 3, page 15-5)

## 15.3 Key Review Topics for Air Transport and Redistribution of Radionuclides

Estimating the potential consequences of a volcanic eruption require evaluating the air transport and subsequent redistribution of the volcanic ash (tephra) in the channels near Yucca Mountain (i.e., Fortymile Wash drainage basin) and the downward migration of radionuclides in the soil and potential uptake by plants and animals.

**1) Airborne transport modeling (contaminated tephra deposited on the surrounding landscape)**

- The DOE model assumed the most likely future eruption to be violent Stombolian from interpretation of youngest volcano near repository site (Lathrop Wells – Valentine et al. 2007aa) - SER Vol. 3 page 15-8

- Violent Strombolian-type eruption is characterized by the development of a sustained, buoyant plume of hot air and volcanic tephra that commonly rises several kilometers [a few miles] above the volcano and, as such, would include such processes as turbulent advection dispersion for dispersal of tephra (Suzuki 1983aa; Jarzemba, et al., 1997aa; Sparks et al 1997aa) – SER Vol. 3 pages 15-8 and 15-10

- The majority of the anticipated wind vectors at the site result in tephra being deposited to the east of Yucca Mountain (SAR Figure 2.3.11-15) and this wind direction provides a source of material for remobilization within the Fortymile Wash catchment basin (SNL 2007ab, Appendix K) SER Vol. 3 Page 15-9

- DOE calculation of tephra and waste deposited at RMEI location at a point is conservative (DOE 2009bk Enclosure 9) – SER Vol. 3 page 15-10

- DOE approaches and parameter values are based on a variety of analog volcanic systems (DOE 2009bm; SNL 2007ab,ae – Ashplume model); (SNL

2007ab,ae; DOE 2009bj or DOE 2009bl[2] Enclosure 3; SNL 2007ab Appendices E and J; DOE 2009bk Enclosure 1) – magma volume and eruptive power) – SER Vol. 3 pages 15-10 thru 15-13)

- NRC and other independent analyses, field investigations and interpretation of information from analog volcanic systems (Andronico et al. 2008aa; Hill et al. 1998aa; Pioli et al. 2008aa; – Ashplume model); (Jarzemba1997aa; Jarzemba et al. 1997aa; Hill and Connor 2000aa; Pioli et al. 2008aa; Leslie et al 2007aa Table 16-1) – magma volume and eruptive power) – SER Vol. 3 pages 15-10 thru 15-13)

- DOE used data from analog volcanic eruptions to support its range for the magma partitioning factor (CRWMS M&O, 2003aa[3]; SNL, 2007ab) and although the NRC staff noted not all the analog volcanoes exhibited significant Strombolian behavior, the DOE assumption to model the entire eruption as violent Strombolian in the performance assessment offsets this limitation (DOE 2009bk Enclosure 8) – SER Vol. 3 pages 15-11 and 15-12

- DOE sensitivity analysis for tephra dispersal and deposit thickness (DOE 2009bk) and NRC independent analysis for variations of deposit thickness (Hill, et al., 1998aa; Winfrey, 2005aa; Janetzke, et al., 2008aa) – SER Vol. 3 page 15-14

- Variation in waste concentration in tephra over the land area representing the RMEI location are not expected to be large (DOE 2009bk Enclosure 2) and NRC staff independent estimates of waste concentrations ((CNWRA, 2007aa, Attachment P–15, p. P15 B–4; Codell 2004aa) – SER Vol. 3 pages 15-14 and 15-15

**2) Tephra redistribution in Fortymile Wash**

- Redistribution influenced by distributary channels and interchannel divides (DOE 2009bk Enclosure 5 Figure 1) – SER Vol. 3 page 15-17

- Critical slope parameters based on measurements at analog sites (SNL 2007av) and noted the parameter uncertainty would not significantly impact model results (DOE 2009bk Enclosure 10) – SER Vol. 3 page 15-18

- Additional model confidence based on published application of the scour-dilution-mixing model to the area around the Lathrop Wells Volcano (Pelletier, et al., 2008aa) – SER Vol. page 15-19

- DOE's approach of basing fluvial redistribution on current channel geomorphology for modeling future fluvial redistribution consistent with

[2] DOE 2009bj is referenced in the SER, however, DOE 2009bl has the exact same RAI response – the more appropriate designation should be DOE 2009bl as this is consistent with the general SER text identifying references DOE 2009bk-bm were evaluated for this section and DOE 2009bj is not referenced – see SER page 15-1; the simplest fix would be to revise the two references to DOE 2009bj to DOE 2009bl on page 15-12 of the SER as both have the same information so it matter littles which is referenced – have no explanation why the same RAI response for tephra appears in two references
[3] The reference in the SER inadvertently left off 'aa' – correctly identified here as 2003aa

information from analog volcanoes such as Parícutin (Segerstrom, 1950aa, 1966aa; Inbar, et al., 1994aa), where original channels were reestablished in the decades following a tephra-fall eruption SER Vol. 3 page 15-20

- Estimates of inhalation of resuspended particulates from tephra-fall deposits or redistributed tephra in fluvial sediments do not underestimate dose based on information in BSC 2006ad; SNL 2007av; DOE 2009bk, Enclosure 4 and independent field measurements that the NRC staff conducted at analog volcanic sites Hill, et al. 2000ab; Benke, et al. 2009aa (SER Vol. 3 page 15-21)

- DOE assessed sheetwash and rilling at the field sites (where DOE measured critical slope values) and provided a justification for why rapid postdepositional erosion was not observed and why it is not expected at Yucca Mountain (DOE 2009bk, Enclosure 6, Sections 1.2–1.4) – SER Vol. 3 page 15-23

- DOE values for scour depth tend to underestimate dilution and overestimate dose (DOE 2009bk, Enclosure 10, Section 1) – SER Vol. 3 page 15-24

- DOE considered the classic dilution-mixing model as appropriate only for tributary systems that discharge into the sea or a lake but not well suited for Fortymile Wash, because it is a tributary-distributary inland drainage system in a desert region (DOE 2009bk, Enclosure 7, Section 1) – SER Vol. 3 page 15-25

- Peer-reviewed journal article (Pelletier, et al., 2008aa) included a site-specific comparison for fluvial redistribution and dilution of tephra from the Lathrop Wells volcano - SER Vol. 3 page 15-26

**3) Downward migration of radionuclides in soil**

- DOE neglected effects of future wetter climates on the basis that wetter climates could increase radionuclide diffusivities in soil, increase vertical migration, reduce the radionuclide concentrations in surface soil layers; NRC found this assumption consistent with wetter climates likely increasing radionuclide migration to deeper soil layers, as identified in Till and Moore (1988aa, Eq. 2) – SER Vol. 3 page 15-29

- Diffusivity rates for radionuclide migration in soils on interchannel divides and in fluvial channels were determined from site-specific field data of Cs-137 profiles (SNL 2007av Appendix A) – SER Vol. 3 page 15-30

- For soils on interchannel divides DOE stated differences in diffusivity for a basaltic tephra deposit on ambient soils would be negligible because tephra thicknesses at the RMEI location would be thin (DOE 2009bk, Enclosure 3) – SER Vol. 3 page 15-31

- Pelletier, et al. (2005aa) published a peer-reviewed journal article that supported use of a diffusion model for radionuclide migration in soil at the Fortymile Wash alluvial fan – SER Vol. 3 page 15-31

**4) Groundwater exposure scenarios**

- DOE determined parameter values using relationships between parameters and measured quantities, which have been published in the scientific literature (e.g., Food and Agriculture Organization and the U.S. Department of Agriculture Natural Resources Conservation Service), and documented its analyses in the Biosphere Model Report (SNL, 2007ac) – SRE Vol. 3 page 15-36

- DOE compared Environmental Radiation Model for Yucca Mountain Nevada (ERMYN) with two other established models that assess radionuclide concentrations in soil, GENII (Napier, et al., 2006aa) and BIOMASS ERB2A (International Atomic Energy Agency, 2003aa) to evaluate the technique used to solve the mathematical model – SER Vol. 3 page 15-36

- An external review by independent experts concluded in SNL (2007ac, Section 7.6) that the overall ERMYN model was a well-constructed, transparent, and complete biosphere modeling tool – SER Vol. 3 page 15-37

## 15.4 References Specific to Air Transport and Redistribution of Radionuclides

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# 16.0 Biosphere Characteristics

Repository releases enter the biosphere from two primary biosphere media: groundwater and soil contaminated with tephra deposits. The more likely pathway for releases from the repository is transport in the groundwater pathway, however, the performance assessment included the far less likely releases of radionuclides from a potential volcanic eruption. In the performance assessment, tephra (often referred to as volcanic ash) is deposited on the ground from postulated volcanic events. DOE's biosphere model then calculated the subsequent transport of these radionuclides within the biosphere through a variety of exposure pathways (e.g., soil, food, water, air) and applied dosimetry modeling to convert the RMEI exposures into annual dose. (see SER Vol. 3, page 16-1)

> *"Exposure pathways in the DOE biosphere model are based on assumptions about residential and agricultural uses of the water and indoor and outdoor activities. These pathways include ingestion, inhalation, and direct exposure to radionuclides deposited to soil from irrigation (SAR Section 2.3.10.1). Ingestion pathways include drinking contaminated water, eating crops irrigated with contaminated water, eating food products produced from livestock raised on contaminated feed and water, eating farmed fish raised in contaminated water, and inadvertently ingesting soil. Inhalation pathways include breathing resuspended soil, aerosols from evaporative coolers, and radon gas and its decay products"* SER Vol. 3 page 16-2

## 16.1 Requirements Specific to Biosphere Characteristics

10 CFR 63.2 defines the reference biosphere as the description of the environment inhabited by the reasonably maximally exposed individual (RMEI). The biosphere characteristics are subject to the specific constraints given in 10 CFR 63.305 (characteristics of the reference biosphere) and in 10 CFR 63.312 (characteristics of the RMEI).

Characteristics of the reference biosphere specified at 10 CFR Part 63.305 are:

*§ 63.305 Required characteristics of the reference biosphere.*

*(a) Features, events, and processes that describe the reference biosphere must be consistent with present knowledge of the conditions in the region surrounding the Yucca Mountain site.*

*(b) DOE should not project changes in society, the biosphere (other than climate), human biology, or increases or decreases of human knowledge or technology. In all analyses done to demonstrate compliance with this part, DOE must assume that all of those factors remain constant as they are at the time of submission of the license application.*

*(c) DOE must vary factors related to the geology, hydrology, and climate based upon cautious, but reasonable assumptions consistent with present knowledge of factors that could affect the Yucca Mountain disposal system during the period of geologic stability, consistent with the requirements for performance assessments specified at § 63.342.*

*(d) Biosphere pathways must be consistent with arid or semi-arid conditions*

Characteristics of the RMEI specified at 10 CFR Part 63.312 are:

*§ 63.312 Required characteristics of the reasonably maximally exposed individual.*

*The reasonably maximally exposed individual is a hypothetical person who meets the following criteria:*

*(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. 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 §§ 63.311 and 63.321;*

*(c) Uses well water with average concentrations of radionuclides based on an annual water demand of 3000 acre-feet;*

*(d) Drinks 2 liters of water per day from wells drilled into the ground water at the location specified in paragraph (a) of this section; and*

*(e) Is an adult with metabolic and physiological considerations consistent with present knowledge of adults.*

## 16.2 Performance Perspectives for the Biosphere Characteristics

Releases of radionuclides to groundwater contributed the most to doses to the RMEI from the ingestion pathway. The inhalation pathway did result in some minor contribution to the overall dose from the contaminated water (i.e., use of evaporative coolers) and contaminated soil from the igneous eruptive scenario.

> *"The NRC staff focused its detailed review on the subset of radionuclides and pathways that are the most risk-significant contributors to the applicant's performance assessment results. An example is provided here to clarify how this approach identifies the most risk-significant contributors to the applicant's results. For the applicant's 1-million-year results presented in SAR Figure 2.4-20(b), the peak total mean annual dose is approximately 0.02 mSv/yr [2 mrem/yr]. Four radionuclides contribute approximately 0.015 mSv/yr [1.5 mrem/yr] (75 percent) to that value. The NRC staff identified these four radionuclides as the most risk-significant contributors because they represent the smallest number of radionuclides that comprise the largest fraction of the peak mean dose. The remaining 17 radionuclides in the applicant's analysis each contributed a small fraction to the peak mean dose. The pathways for these four radionuclides were then individually evaluated to identify the subset of pathways that contributed the largest fraction to the dose contribution from the radionuclide using information provided in SAR Table 2.3.10-11. For example, Pu-242 is responsible for 30 percent of the applicant's peak mean dose. The NRC staff evaluated the*

*pathways through which Pu-242 contributed to the dose and found that the inhalation of particulates pathway was responsible for 51 percent of the Pu-242 dose, the inhalation of evaporative cooler aerosols pathway was responsible for 24 percent of the Pu-242 dose, and the drinking groundwater pathway was responsible for 19 percent of the Pu-242 dose. Twelve other pathways are responsible for the remaining 6 percent of the Pu-242 dose; therefore, three pathways were identified as being the most risk significant for Pu-242. This example illustrates the NRC staff's approach to identifying the radionuclides and their pathways that are the most risk significant to the applicant's performance assessment calculation.*

*SER Table 16-1 contains the radionuclides and their pathways that are the most risk-significant contributors to the applicant's performance assessment dose results for the time period of 10,000 years following disposal, as specified by 10 CFR 63.311(a)(1). SER Table 16-2 contains the radionuclides and their pathways that are the most risk-significant contributors to the applicant's performance assessment dose results for the time period after 10,000 years following disposal but within the period of geologic stability, as described in 10 CFR 63.311(a)(2). The radionuclides listed in SER Tables 16-1 and 16-2 include radionuclides found to be important contributors to dose results in prior independent NRC performance assessment results, as identified in NRC (2005aa, Volume 2, Appendix D)."* (SER Vol. 3 page 16-5 and 16-6)

**Table 16-1. Exposure Pathways and Radionuclides Found To Be the Most Risk Significant in the DOE Performance Assessment for the 10,000-Year Simulation Period**

| Radionuclide* | Source of Radionuclides† | Route of Exposure‡ | Primary Pathways‡ |
|---|---|---|---|
| Tc-99 | Estimated Releases to Groundwater | Ingestion | 42% drinking water<br>37% animal product |
| C-14 | | Ingestion | 59% fish<br>22% drinking water |
| Pu-239 | | Inhalation | 50% particulates<br>24% evaporative cooler aerosol |
| | | Ingestion | 19% drinking water |
| I-129 | | Ingestion | 60% drinking water<br>28% animal products |

*Radionuclides presented in order of their contribution to the DOE peak total mean annual dose results in SAR Figure 2.4-20.

† Modeling cases that contribute most to the DOE total mean annual dose are based on release to groundwater as shown in SAR Figure 2.4-18 and SAR Section 2.4.2.2.1.2.

‡ Routes of exposure and primary pathways from SAR Table 2.3.10-11. Various pathways not listed contribute the remaining percentage of each radionuclide dose.

**Table 16-2. Exposure Pathways and Radionuclides Found To Be the Most Risk Significant in the DOE Performance Assessment for the 1-Million-Year Simulation Period**

| Radionuclide* | Source of Radionuclides† | Route of Exposure‡ | Primary Pathways‡ |
|---|---|---|---|
| Pu-242 | Estimated Releases to Groundwater | Inhalation | 51% particulates<br>24% evaporative cooler aerosols |
| | | Ingestion | 19% drinking water |
| Np-237 | | Inhalation | 35% evaporative cooler aerosols<br>21% particulates |
| | | Ingestion | 29% drinking water |
| Rn-222 (from decay of Rn-226) | | Inhalation | 74% radon |
| I-129 | | Ingestion | 60% drinking water<br>28% animal products |

*Radionuclides presented in order of their contribution to the DOE peak total mean annual dose results in SAR Figure 2.4-20.
† Modeling cases that contribute most to the DOE total mean annual dose are based on release to groundwater as shown in SAR Figure 2.4-18 and SAR Section 2.4.2.2.1.2.
‡ Routes of exposure and primary pathways from SAR Table 2.3.10-11. Various pathways not listed contribute the remaining percentage of each radionuclide dose.

## 16.3 Key Review Topics for the Biosphere Characteristics

The biosphere characteristics include the exposure scenarios (how humans contact the radionuclides in the biosphere), values impacting the transport of radionuclides that enter the biosphere (e.g., soil-to-plant transfer parameters), and finally human exposure (e.g., human activities that lead to exposure such as drinking water containing radionuclides) including dosimetry (methodology for estimating radionuclide dose).

**1) Exposure Scenarios (groundwater and volcanic ash)**

- DOE's dose to the RMEI involves three routes of exposure: external exposure, inhalation, and ingestion. The inhalation dose portion of the applicant's conceptual model includes RMEI inhalation of radionuclides in (i) resuspended soil particles, (ii) gaseous emissions from the soil and their radioactive decay products, and (iii) aerosols generated by evaporative coolers. The ingestion dose portion of the applicant's conceptual model includes (i) drinking water; (ii) crops, including leafy vegetables, other vegetables, fruits, and grains; (iii) animal products, including meat, poultry, milk, and eggs; (iv) freshwater fish; and (v) soil. The meat category is a combination of all edible portions of beef, pork, and wild game (BSC, 2005ab) – SER Vol. 3 page 16-9

- Both NRC's independent analyses (LaPlante and Poor 1997aa) and DOE's analyses (SAR Section 2.3.10.5.1.1) suggest that future climate states, which are expected to be cooler and wetter than the current climate, would result in the RMEI using less irrigation water, and would, therefore, lower the amount of radionuclides deposited to soils and lower the calculated RMEI dose (SER Vol. 3 pages 16-11 and 16-12)

**2) Biosphere transport pathways**

- RMEI inhalation of resuspended particulates is the predominant pathway for the volcanic ash exposure scenario's biosphere dose conversion factors for Pu-239 and Pu-240 (SAR Table 2.3.10-15) and is consistent with the NRC independent analysis (NRC, 2005aa; LaPlante and Poor, 1997aa) – SER Vol. 3 page 16-12

- DOE's references for transfer factor input parameters include the most extensive international literature compilation of scientific data on the topic (International Atomic Energy Agency, 1994aa) – SER Vol. 3 pages 16-13 thru 16-17

- Comparison of DOE's transfer factor values for risk significant radionuclides (i.e., technetium, iodine, neptunium, americium, and plutonium) in BSC (2004ap) with values independently selected from the available literature and reported in prior NRC documents and analyses (NRC, 1992ae; LaPlante and Poor, 1997aa) – SER Vol. 3 pages 16-13 thru 16-17

- NRC independent analyses indicate the magnitude of DOE's derived values for mass loading produce dust inhalation results that are greater than results based on independently derived mass loading and other applicable input parameters, as identified in Leslie, et al. (2007aa, Table 17-1) – SER Vol. 3 page 16-20

- DOE reviewed literature that included measured dust levels of volcanic ash resuspended in air for ambient and surface-disturbing conditions at various sites where volcanoes had recently erupted (within 5 years) and also compared the relevance of each analog site (including the Soufrière Hills Volcano in Montserrat, British West Indies, and the Mt. Spurr Volcano in Alaska) to expected conditions in the Yucca Mountain region – SER Vol. 3 page 16-20

**3) Human exposure and dosimetry**

- DOE used Year 2000 census data from the Amargosa Valley census county division (Bureau of the Census, 2002aa) for population distribution by age, work status and hours worked, commute time, and industry of employment. DOE also used detailed national survey data on activity time budgets from Klepeis, et al. (1996aa) and EPA (1997aa) to assign the fraction of time spent inside a residence; outdoors; in a vehicle; and at stores, restaurants, and other indoor locations (BSC 2005ab) – SER Vol. 3 page 16-24

- For the inhalation exposure model DOE combined breathing rate information for adults by gender and level of physical activity from International Commission on Radiological Protection (1994aa) with census demographic information for Amargosa Valley to derive population gender-weighted breathing rates – SER Vol. 3 page 16-25

- For the ingestion exposure model, DOE food consumption rates are mean values based on the 1997 survey of Amargosa Valley residents consistent with 10 CFR 63.312(b) that directs DOE to use projections based upon surveys of Amargosa Valley residents – SER Vol. 3 page 16-27

- The DOE biosphere model uses dose coefficients from the Federal Guidance Report 13 (EPA, 1999aa), which uses tissue-weighting factors recommended in International Commission on Radiological Protection, Publication 60 (1991aa) to calculate effective dose from both internal and external radiation sources – SER Vol. 3 page 16-27

- NRC confirmatory calculations regarding the dose calculation showing consistent results (only 2% difference) – SER Vol. 3 page 16-29

## 16.4 References Specific to Biosphere Characteristics

BSC. 2005ab. "Characteristics of the Receptor for the Biosphere Model." ANL–MGR–MD–000005. Rev. 04. ML090720248. Las Vegas, Nevada: Bechtel SAIC Company, LLC.

EPA. 1999aa. "Federal Guidance Report 13, Cancer Risk Coefficients for Environmental Exposure to Radionuclides." EPA 402–R–99–001. Washington, DC: U.S. Environmental Protection Agency.

EPA. 1997aa. "Exposure Factors Handbook, Volume III, Activity Factors." EPA/600/P–95/002Fc. Washington, DC: U.S. Environmental Protection Agency.

International Commission on Radiological Protection. 1994aa. "Human Respiratory Tract Model for Radiological Protection." ANL–MGR–MD–000005. Rev. 4. DIRS 153705. *Annals of the ICRP.* Publication 66. Vol. 24, No. 1-3. New York City, New York: Pergamon Press.

International Commission on Radiological Protection. 1991aa. "1990 Recommendations of the International Radiological of Commission Protection." ANL–MGR–MD–000005. Rev. 4. DIRS 153705. *Annals of the ICRP*. Publication 60. Vol. 21, No. 1-3. New York City, New York: Pergamon Press.

Klepeis, N.E., A.M. Tsang, and J.V. Behar. 1996aa. "Analysis of the National Human Activity Patter Survey (NHAPS) Respondents From a Standpoint of Exposure Assessment, Percentage of Time Spent, Duration, and Frequency of Occurrence for Selected Microenvironments by Gender, Age, Time-of-Day, Day-of-Week, Season, and U.S. Census Region—Final Report." EPA/600/R–96/074. ANL–MGR–MD–000005. Rev. 4. DIRS 159299. Washington, DC: U.S. Environmental Protection Agency, Office of Research and Development.

LaPlante, P.A. and K. Poor. 1997aa. "Information and Analyses to Support Selection of Critical

Groups and Reference Biospheres for Yucca Mountain Exposure Scenarios." CNWRA 97-009. ML040200056. San Antonio, Texas: CNWRA.

Leslie, B., C. Grossman, and J. Durham. 2007aa. "Total-system Performance Assessment (TPA) Version 5.1 Module Descriptions and User Guide." Rev. 1. ML072710060. San Antonio, Texas: CNWRA.

NRC. 2005aa. NUREG–1762, "Integrated Issue Resolution Status Report." Vol. 2. Rev. 1. ML051360241. Washington, DC: NRC.

NRC. 1992ae. NUREG–5512, "Residual Radioactive Contamination From Decommissioning: Technical Basis for Translating Contamination Levels To Annual Total Effective Dose Equivalent—Final Report." Vol. 1. ML052220317. Washington, DC: NRC

# 17.0 Compliance with Individual Protection Standards

Compliance with the individual protection standard is evaluated with the TSPA's probability-estimated dose for the exposure for the reasonably-maximally exposed individual (RMEI).

> *"[t]he U.S. Department of Energy (DOE) provided in its license application [Safety Analysis Report (SAR) Section 2.4.2 (DOE, 2008ab)] its basis for demonstrating compliance with the individual protection standards for the initial 10,000 years after closure and the period after 10,000 years up to 1 million years. DOE conducted an analysis, through its Total System Performance Assessment (TSPA) computer model, that evaluates the behavior of the high-level waste repository in terms of an annual dose due to potential releases from the repository. The performance assessment provides a method to evaluate the range of features (e.g., geologic rock types, waste package materials), events (e.g., earthquakes, igneous activity), and processes (e.g., corrosion of metal waste packages, sorption of radionuclides onto rock surfaces) that are relevant to the behavior of a repository at Yucca Mountain."* - SER Vol. 3 page 17-1

## 17.1 Requirements Specific to Compliance with Individual Protection Standards

> *"The regulations at 10 CFR 63.311 (Individual Protection Standard after Permanent Closure) require that the annual dose must not exceed 0.15 mSv/yr [15 mrem/yr] during the initial 10,000 years following disposal and not exceed 1.0 mSv/yr [100 mrem/yr] after 10,000 years up to 1 million years. The regulations at 10 CFR 63.113(b) specify that a performance assessment must be used to demonstrate compliance with the individual protection dose limit and set forth requirements for the performance assessment analysis at 10 CFR 63.114 and 63.342.*
>
> *
> *
> *
>
> *The requirements at 10 CFR 63.311 also specify how the performance assessment model is used to estimate the annual dose to the RMEI. In general, DOE is required to use the performance assessment to*
>
> - *Demonstrate that the arithmetic mean (i.e., average) of the annual dose over the initial 10,000 years following disposal is no greater than 0.15 mSv [15 mrem] per 10 CFR 63.303 and 63.311(a)(1)*
>
> - *Demonstrate that the arithmetic mean (i.e., average) of the annual dose after 10,000 years up to 1 million years (geological stability) is no greater than 1.0 mSv [100 mrem] per 10 CFR 63.303 and 63.311(a)(2)"*
>
> SER Vol. 3 pages 17-1 and 17-2

## 17.2 Performance Perspectives for Compliance with Individual Protection Standards

The TSPA includes scenarios for igneous activity, seismic events, and early failures with the largest contributors to the individual dose coming from the seismic ground motion and the igneous intrusion scenarios.

> *"DOE has identified three distinct event scenario classes (also referred to as event classes or scenario classes) that are included in its TSPA model to demonstrate compliance with the individual protection standard: (i) early failures, (ii) seismic events, and (iii) igneous events. DOE has used two modeling cases within each scenario class to represent specific aspects of the scenario. The early failure scenario class is composed of an early waste package failure modeling case and an early drip shield failure modeling case. The seismic scenario class is composed of a seismic ground motion modeling case and a seismic fault displacement modeling case. The igneous scenario class is composed of an igneous intrusion modeling case and a volcanic eruption modeling case."*
> (SER Vol. 3 page 17-3)
>
> *"The two modeling cases (i.e., igneous intrusion modeling case and seismic ground motion modeling case) that result in the greatest number of failed waste packages are the largest contributors to the overall average annual dose curve"* (SER Vol. 3 page 17-7)

## 17.3 Key Review Topics for Compliance with Individual Protection Standards

The NRC staff evaluation considered the DOE's three scenario classes (i.e. igneous, seismic, and early failures) in terms of their contribution to the overall dose curves for determining compliance with the individual protection standards (i.e., annual average dose to the RMEI).

**1) Igneous Scenario class probability and results**

- The mean recurrence frequency for the volcanic eruption modeling case is $1.4 \times 10^{-9}$ per year and a mean frequency of $1.7 \times 10^{-8}$ per year for the igneous intrusion modeling case (SAR p. 2.4-49) – SER Vol. 3 pages 17-4 and 17.5

- The igneous intrusion modeling case is the second largest contributor to the overall average annual dose (i.e., summation of average annual dose from all scenario classes) in the 10,000-year period and the largest contributor to the overall average annual dose after 10,000 years (SAR Figure 2.4-18) – SER Vol. 3 page 17-5)

**2) Seismic scenario class probability and results**

- The DOE model described seismic ground motion events as a Poisson process, with events distributed in time with a mean recurrence frequency of $4.287 \times 10^{-4}$ per year [corresponding to the frequency of events with a peak ground velocity exceeding 0.219 m/s [0.72 ft/s] (SAR Section 2.4.2.1.6, p. 2.4-50 and CRWMS M&O 1998aa) – SER Vol. 3 page 17-6

- The seismic ground motion modeling case is second only to the igneous intrusion modeling case in overall significance to the overall average annual dose curve and is the largest contributor to the overall average annual dose curve for the period after 1,500 years through 20,000 years (SAR p. 2.4-61) – SER Vol. 3 page 17-7

**3) Early Failure Scenario class**

- The early failure scenario class contributes on the order of 1 percent or less to the overall average annual dose curve (SAR Figure 2.4-18) – SER Vol. 3 page 17-5)

**4) Credible representation of repository performance**

- NRC staff reviewed the TSPA documentation in SAR Volume 2 and in the TSPA GoldSim computer model and associated computer files (including intermediate results saved in the GoldSim output files) that included NRC independent analysis with its performance assessment model (CNWRA and NRC 2008aa; and NRC 2005aa, Appendix D).– SER Vol. 3 page 17-8

- NRC evaluated dose results related to groundwater releases (including aspects such as seepage flux [i.e., flux of water dripping into drifts], damage to the drip shields and waste packages, flux of water entering the waste packages, release of radionuclides from the waste package, transport of radionuclides in the unsaturated and saturated zone, and annual dose to the RMEI) that included documentation of NRC's independent confirmatory calculation (NRC and CNWRA 2014aa) – SER Vol. 3 pages 17-9 thru 17-30

- NRC evaluated dose results related to releases from the volcanic eruption modeling case (including such aspects as number of waste packages impacted, dispersal of tephra or volcanic ash, and annual dose to the RMEI) that included documentation of NRC's independent confirmatory calculation (NRC and CNWRA 2014aa) – SER Vol. 3 pages 17-30 thru 17-34

**5) Statistical stability of the average annual dose curve**

- DOE estimated 95 percent confidence bounds for the average annual dose using information from the replicates and a t-distribution with 2 degrees of freedom, as described in SNL (2008ag, Section J4.10) – SER Vol. 3 page 17-34

- The peak of the overall average annual dose curve is approximately 0.003 mSv/yr [0.3 mrem/yr] over the 10,000-year time period {dose limit of 0.15 mSv/yr [15 mrem/yr] for this period} and is approximately 0.02 mSv/yr [2 mrem/yr] over the 1-million-year period {dose limit of 1.0 mSv/yr [100 mrem/yr] for this period} as shown in SAR Figure 2.4-10 (SER Vol. 3 page 13-35)

- Model updates from TSPA Model v5.000 to v5.005 caused only a moderate change in the magnitude of the overall average annual dose; the same conclusions with respect to average annual dose stability are expected to apply to both versions v5.000 and v5.005 (i.e.; the model updates do not cause different numerical model behavior in regard to statistical stability); for example, see SNL 2008ag, Figures 7.3.1-17(a) to 7.3.3-13(a) – SER Vol. 3 page 17-36

## 17.4 References Specific to Compliance with Individual Protection Standards

CRWMS M&O. 1998aa. “Probabilistic Seismic Hazard Analyses for Fault Displacement and Vibratory Ground Motion at Yucca Mountain, Nevada.” WBS 1.2.3.2.8.3.6. ML090690430. Las Vegas, Nevada: CRWMS M&O.

CNWRA and NRC. 2008aa. “Risk Insights Derived From Analyses of Model Updates in the Total-system Performance Assessment Version 5.1 Code.” ML082240343. San Antonio, Texas: CNWRA.

NRC. 2005aa. NUREG–1762, “Integrated Issue Resolution Status Report.” Rev. 1. ML051360241. Washington, DC: NRC.

NRC and CNWRA. 2014aa. “Documentation of Analyses in Support of the Safety Review of DOE's Total System Performance Assessment Calculations for a Proposed Repository at Yucca Mountain.” ML101450306. Washington, DC: NRC.

SNL. 2008ag. “Total System Performance Assessment Model/Analysis for the License Application.” MDL–WIS–PA–000005. Rev. 00. AD 01, ERD 01, ERD 02, ERD 03, ERD 04. ML090790353, ML 090710331, ML 090710188. Las Vegas, Nevada: Sandia National Laboratories

# 18.0 Compliance with Human Intrusion Standards

Compliance with the human intrusion standards involve estimating repository performance to a postulated human intrusion that involves drilling into a single waste package without recognition by the drillers.

> *"The geologic record provides a basis for evaluating the likelihood of geologic processes and events, but there is no similar record of extended duration that can be used to constrain either the probability that human intrusion could occur or the characteristics of such intrusion. Regulations specify that the potential effects of human intrusion on waste isolation must be considered when evaluating repository performance. The NRC staff's review evaluates whether the repository can adequately perform if its barriers are breached by a human intrusion."* - SER Vol. 3 page 18-1

## 18.1 Requirements Specific to Compliance with Human Intrusion Standards

> *"To evaluate human intrusion, the regulations establish dose limit requirements [10 CFR 63.321(b)], requirements specific to the human intrusion scenario [10 CFR 63.321(a) and 63.322], and requirements for conducting the performance assessment [10 CFR 63.113(d), 63.114, 63.303, and 63.342]. Accordingly, the U.S. Department of Energy (DOE or the applicant) must evaluate when a human intrusion might occur and the consequences of the human intrusion, in accordance with the previously noted regulatory requirements. In particular, the individual protection standard for human intrusion requires the applicant to*
>
> - *Determine the earliest time after disposal that the waste package would degrade sufficiently that a human intrusion could occur without the drillers recognizing it [10 CFR 63.321(a)]*
>
> - *Assume for the human intrusion scenario that (i) there is a single human intrusion as a result of exploratory drilling for groundwater, (ii) the intruders drill a borehole directly through a degraded waste package into the uppermost aquifer underlying the Yucca Mountain repository, (iii) the drillers use the common techniques and practices that are currently employed in exploratory drilling for groundwater in the region surrounding Yucca Mountain, (iv) careful sealing of the borehole does not occur— instead, natural degradation processes gradually modify the borehole, (v) no particulate waste material falls into the borehole, (vi) the exposure scenario includes only those radionuclides transported to the saturated zone by water (e.g., water enters the waste package, releases radionuclides, and transports radionuclides by way of the borehole to the saturated zone), and (vii) no releases are included that are caused by unlikely natural processes and events [10 CFR 63.322]*
>
> - *Demonstrate that there is a reasonable expectation that the reasonably maximally exposed individual (RMEI) receives, as a result of the human intrusion, no more than the following annual dose: 0.15 mSv [15 mrem] for 10,000 years following disposal and 1.0*

*mSv [100 mrem] after 10,000 years but within the period of geologic stability [10 CFR 63.321(b)]"*

(SER Vol. 3 pages 18-1 and 18.2)

## 18.2 Performance Perspectives for Compliance with Human Intrusion Standards

*"The applicant determined that there is only a 0.0001 percent chance that the drip shield will fail by corrosion before approximately 230,000 years under the nominal scenario class, which represents "normal" conditions (see SER Section 2.2.1.4.1 for discussion of the nominal scenario). The applicant also determined that the waste package has only a 5 percent chance of failure (i.e., significant degradation or thinning of the walls of the waste package) from general corrosion prior to 600,000 years. On the basis of these results, the applicant selected 200,000 years as the earliest time the waste package would degrade sufficiently that a human intrusion could occur without the drillers recognizing it. The applicant considered this a conservative approach because the waste package is estimated to have experienced limited degradation due to corrosion (i.e., waste package to be substantially intact) by that time."* (SER Vol. 3 page 18-3)

*"DOE presented the dose curve for the human intrusion scenario in SAR Figure 2.4-11. The peak of the mean dose curve is approximately 0.0001 mSv/yr [0.01 mrem/yr] shortly after the time of the intrusion (i.e., 200,000 years). DOE's estimated dose is on the order of 10,000 times less than the dose limit of 1 mSv/yr [100 mrem/yr] for the period after 10,000 years."* (SER Vol. 3 page 18-9)

## 18.3 Key Review Topics for Compliance with Human Intrusion Standards

Evaluation of human intrusion considered DOE's specification for the timing of the event, representation of the event (e.g., amount of water entering the intrusion borehole, transport of radionuclides through the unsaturated zone down to the saturated zone) and estimate of the dose.

**1) Timing of the human intrusion event**

- DOE determined there was limited damage to the drip shield and waste package from corrosion processes prior to the assumed time for the human intrusion event of 200,000 years (SAR Section 2.4.3.2; DOE 2009bj Enclosure 1, Figures 3, 4, 7, 9, and 10) – SER Vol. 3 pages 18.3 and 18.4

- DOE evaluated other events that might affect the timing of the human intrusion event (e.g., early undetected defects, igneous disruptive events, and seismic events) and determined that either the likelihood was less than the limit for likely events or the damage would not be sufficient to prevent the driller from recognizing that a metal object had been contacted (SAR Section 2.4.3.2.2, pp. 2.4-303 and 304) - SER Vol. 3 pages 18-3

**2) Representation of human intrusion event**

- DOE described how the amount of water that enters the waste package through the borehole is limited to the seepage entering the borehole (deep percolation is assumed to pass directly into the borehole opening); other processes (e.g., drift seepage water splashing on the waste package surface and entering the waste package through the hole created by the borehole) were evaluated and determined to not significantly add to the quantity of water entering the borehole, as described in DOE (2009bj, Enclosure 4, Section 1.1) – SER Vol. 3 page 18-6

- Although water in the borehole is estimated to take approximately 3 years to move through the unsaturated zone to the saturated zone, nonsorbing (I-129) and sorbing (Np-237) radionuclides are estimated to be delayed approximately 1,250 and 64,000 years by matrix diffusion, respectively, as outlined in DOE 2009bj, Enclosure 5, p. 8); DOE (2009cp, p. 2) explained this effect is due to the large effective surface area for communication between the fracture and the matrix in the degraded borehole (that is filled with rock debris) and along the borehole (SER Vol. 3 page 18-6)

**3) Annual dose estimate**

- DOE provided a comparison with an alternative model [i.e., the analytical solution of Sudicky and Frind described in DOE (2009bj, Enclosure 5, Figure 2)] to support the approach for matrix diffusion in the borehole (SER Vol. 3 page 18-10)

- DOE considered a range of tests (i.e., different combinations of sampled values, increased aleatory sample size, and reduced timesteps), all of which resulted in dose curves that do not change the overall result that the peak dose is on the order of 0.0001 mSv/yr [0.01 mrem/yr] {see SAR Figures 2.4-160(a) and 2.4-161 and SNL [2008ag, Figures 7.3.3-10(a) and 7.3.3-11(a)]} – SER Vol. 3 page 18-11

- The human intrusion scenario (SAR Figure 2.4-159) and the waste package early failure modeling case [SAR Figure 2.4-18(b)] result in peak doses over the million-year period on the order of .0001 mSv/yr [0.01 mrem/yr] consistent with the human intrusion scenario considering one waste package and the waste package early failure modeling case considers approximately one failed waste package (SER Vol. 3 page 18-11)

## 18.4 References Specific to Compliance with the Human Intrusion Standards

DOE. 2009bj. “Yucca Mountain—Response to Request for Additional Information Regarding License Application (Safety Analysis Report Section 2.4.4) Safety Evaluation Report Vol. 3, Chapters 2.2.1.4.1, 2.2.1.4.2, and 2.2.1.4.3, Set 1.” Letter (July 29) J.R. Williams to J.H. Sulima (NRC). ML092110472. Washington, DC: DOE, Office of Technical Management.

DOE. 2009cp. “Yucca Mountain—Supplemental Response to Request for Additional Information Regarding License Application (Safety Analysis Report Section 2.4.3), Safety Evaluation Report Vol. 3, Chapter 2.2.1.4.2, Set 1.” Letter (October 20) J.R. Williams to J.H. Sulima (NRC). ML092940188. Washington, DC: DOE, Office of Technical Management.

SNL. 2008ag. "Total System Performance Assessment Model/Analysis for the License Application." MDL–WIS–PA–000005. Rev. 00. AD 01, ERD 01, ERD 02, ERD 03, ERD 04. ML090790353. Las Vegas, Nevada: Sandia National Laboratories.

# 19.0 Compliance with the Separate Groundwater Protection Standards

*"The NRC's regulations provide separate standards to protect the groundwater resources in the vicinity of Yucca Mountain and specify the approach to be taken to estimate the concentration of radionuclides in groundwater. This approach for groundwater protection (10 CFR 63.331) is similar to that used in estimating dose to the reasonably maximally exposed individual (RMEI) (10 CFR 63.311, 63.312). There are three distinct groups of radionuclides evaluated under groundwater protection: (i) radionuclides that are characterized as alpha emitters (e.g., Np-237) (this group explicitly excludes radon and uranium); (ii) radionuclides that are characterized as beta- and photon-emitting radionuclides (e.g., I-129, Tc-99); and (iii) the combined concentration of Ra-226 and Ra-228 released from the repository and the natural background levels of Ra-226 and Ra-228 in the groundwater. There are a number of similarities in the performance assessment used for demonstrating compliance with the individual protection standard and the performance assessment used to demonstrate compliance with the separate groundwater protection standards, including weighting the results by the probability of occurrence."* - SER Vol. 3 page 19-1

## 19.1 Requirements Specific to Compliance with the Separate Groundwater Protection Standards

*"Specific regulatory requirements related to DOE's demonstration of compliance with separate groundwater protection standards follow:*

*Performance Assessment for Groundwater Protection*

- *The performance assessment must be conducted in accordance with the general requirements for the performance assessment covering the initial 10,000 years specified in 10 CFR 63.114, 63.303, and 63.342.*

*Representative Volume*

- *The representative volume is the volume of groundwater that would be withdrawn annually from an aquifer containing less than 10,000 mg of total dissolved solids per liter of water [10 CFR 63.332(a)].*

- *DOE must determine the concentration of radionuclides that will be released from the Yucca Mountain repository that will be in the representative volume of groundwater for comparison with the separate groundwater protection standards [10 CFR 63.332(a)].*

- *DOE must determine the position and dimensions of the representative volume using average hydrologic characteristics, which must include the highest concentration level in the plume of contamination in the accessible environment [10 CFR 63.332(a)(1 and 2)].*

- *The representative volume contains 3,000 acre-ft [3.7 X $10^9$ L] of water [10 CFR 63.332(a)(3)].*

*Separate Standards for Groundwater Protection (10 CFR 63.331, Table 1)*

- *The combined concentration of Ra-226 and Ra-228 from repository releases cannot exceed 5 pCi/L (including natural background radiation presently in groundwater at Yucca Mountain).*

- *For gross alpha activity (including Ra-226 but excluding radon and uranium), the combined concentration from repository releases and natural background radiation presently in groundwater at Yucca Mountain must be less than 15 pCi/L. (Np-237 is an example of an alpha-emitting radionuclide.)*

- *The combined concentration of beta- and photon-emitting radionuclides from repository releases cannot exceed 0.04 mSV [4 mrem] per year to the whole body or any organ {on the basis of drinking 2 L [0.53 gal] of water per day from the representative volume}. (Tc-99 and I-129 are examples of beta- and photon-emitting radionuclides.)*

- *DOE must determine background concentrations of specific radionuclides in groundwater as identified previously for Ra-226, Ra-228, and gross alpha activity.*

*The performance assessment for compliance with the individual protection standard is consistent with the performance assessment used to evaluate compliance with the groundwater protection standards (i.e., differences are due to the regulatory requirement that unlikely events are not to be included in the performance assessment used for groundwater protection).”*

(SER Vol. 3 pages 18-1 and 18.2)

## 19.2 Performance Perspectives for Compliance with the Separate Groundwater Protection Standards

Compliance with the separate groundwater protection standards used the same TSPA used for individual protection to determine the concentration of radionuclides in the representative volume of groundwater. DOE simplified the determination of the concentration of radionuclides in groundwater by assuming all the releases were captured in the representative volume.

*“DOE used the same performance assessment model for evaluating compliance with the separate groundwater protection standards as it used for the individual protection standards in the sense that the model abstractions for flow paths in the saturated zone and radionuclide transport in the saturated zone are the same. However, DOE excluded the consideration of unlikely FEPs from the performance assessment used for groundwater protection (i.e., igneous activity and low probability seismic events are excluded).”* (SER Vol. 3 page 18-3)

## 19.3 Key Review Topics for Compliance with the Separate Groundwater Protection Standards

The evaluation of compliance with the separate groundwater protection standard focused on the representative volume and DOE's determination of the concentration of radionuclides in groundwater because the performance assessment used for individual protection, which was evaluated previously, was also used for groundwater protection calculations.

**1) Representative volume**

- DOE provided a detailed depiction of the cross section of the plume at the compliance location to support the dimensions of the representative volume, which was based on numerous particle tracks (DOE 2009bj, Enclosure 7, Figure 1) – SER Vol. 3 pages 19-4 and 19-5

- The two values DOE estimated from the detailed analysis for the cross-sectional area of the representative volume {one a rectangular shape of 726,000 $m^2$ [7.8 million $ft^2$] and the other an irregular shape of 435,000 $m^2$ [4.7 million $ft^2$]} bound the value of 600,000 $m^2$ [6.4 million $ft^2$] DOE specified for the representative volume (SER Vol. 3 page 19-6

**2) Concentration of radionuclides in groundwater**

- DOE determined the average concentration of radionuclides, due to repository releases, by assuming the annual releases of radionuclides were all included in the representative volume of 3,000 acre-ft [$3.7 \times 10^9$ L] and determined the dose to the whole body and individual organs for the beta- and photon-emitting radionuclides on the basis of drinking 2 L [0.53 gal] – SER Vol. 3 pages 19-6 and 19-7

## 19.4 References Specific to Compliance with the Separate Groundwater Protection Standards

DOE. 2009bj. "Yucca Mountain—Response to Request for Additional Information Regarding License Application (Safety Analysis Report Section 2.4.4) Safety Evaluation Report Vol. 3, Chapters 2.2.1.4.1, 2.2.1.4.2, and 2.2.1.4.3, Set 1." Letter (July 29) J.R. Williams to J.H. Sulima (NRC). ML092110472. Washington, DC: DOE, Office of Technical Management.

# 20.0 Expert Elicitation

Expert elicitation was used by DOE to complement sources of scientific and technical information in three specific areas – probabilistic volcanic hazards, probabilistic seismic hazards, and saturated zone flow and transport.

> *"Expert elicitation is a formal, structured, and well-documented process for obtaining the judgments of multiple experts. The U.S. Nuclear Regulatory Commission (NRC) routinely accepts, for review, expert judgments used to evaluate and interpret the factual bases of safety analyses. The NRC staff recognizes that DOE could elect to use the subjective judgments of experts, or groups of experts, to interpret data and address technical issues and inherent uncertainties when assessing the long-term performance of a geologic repository. In its SAR, DOE used the results of three formal expert elicitations to complement and supplement other sources of scientific and technical information, such as data collection, analyses, and experimentation."* - SER Vol. 3 page 20-1

## 20.1 Requirements Specific to Expert Elicitation

NRC has specific requirements for conducting expert elicitations independent from the specific technical or scientific area of the elicitation.

> *The regulatory requirement in 10 CFR 63.21(c)(19) provides that the SAR must include an explanation of how expert elicitation was used. In 1996, the NRC staff published guidance for the use of expert elicitation in NUREG–1563 (NRC, 1996aa). NUREG–1563 provides general guidelines for deciding whether a formal expert elicitation would be useful and suggests a nine-step procedure that could serve as one acceptable process to conduct an elicitation. The guidance explicitly states that the suggested procedure was not provided with the intent that it be rigidly applied. Rather, the guidance in NUREG–1563 (NRC, 1996aa, p. 22) provides that the suggested procedure "…should be viewed as a general framework for a formal elicitation that would be acceptable to the NRC staff."*
> (SER Vol. 3 page 20-1)

## 20.2 Performance Perspectives for Expert Elicitation

DOE used three expert elicitations: the Probabilistic Volcanic Hazard Assessment (PVHA), the Probabilistic Seismic Hazard Assessment (PSHA), and the Saturated Zone Flow and Transport Expert Elicitation (SZEE). The PVHA developed a probability distribution of the annual frequency of intersection of a basaltic dike with the proposed repository footprint based on 10 experts' probability estimates (SER Vol. 3 page 20-2). The PSHA results developed (1) ground motion hazard curves that express increasing levels of ground motion as a function of the annual probability that the ground motion will be exceeded, including estimates of uncertainty and (2) probabilistic fault displacement hazard curves for nine demonstration points at or near Yucca Mountain that represent a range of faulting and related fault deformation conditions in the subsurface and near the sites of proposed surface facilities (SER Vol. 3 page 20-4). The SZEE developed a recommended range of values for vertical anisotropy, dispersivity, and specific discharge that DOE later used, along with other sources of information, to characterize the uncertainty of flow and transport of radionuclides beneath and down gradient of Yucca Mountain (SER Vol. 3 page 20-4).

## 20.3 Key Review Topics for Expert Elicitation

The evaluation of expert elicitation focused on the techniques and process DOE used in conducting the three expert elicitations (PVHA, PSHA, and SZEE). The technical review of the technical information supporting the elicitations were evaluated in Section 3 (Identification of Events With Probabilities Greater Than $10^{-8}$ Per Year) for the PVHA, Section 5 (Mechanical Disruption of Engineered Barriers) for the PSHA, and Section 11 (Flow Paths in the Saturated Zone) for the SZEE.

**1) Probabilistic Volcanic Hazard Assessment (PVHA)**

- DOE adequately documented the PVHA (CRWMS M&O, 1996aa) and a subsequent update (PVHA-U; SNL, 2008ah) that was considered confirmatory of the original PVHA technical basis (DOE 2009av and Boyle 2008aa) – SER Vol. 3 pages 20-2, 20-3, and 20-8

- DOE published the results from the updated PVHA, or PVHA-U, after it submitted the SAR (SNL, 2008ah) thus DOE did not directly use the PVHA-U results in its SAR or in direct support of models or parameters in the TSPA - DOE referred to the PVHA-U results as confirming the 1996 PVHA results (SER Vol. 3 page 20-8)

- Although the PVHA included 10 experts, the NRC noted that a greater balance of panel experts would have encompassed a wider range of viewpoints (NRC, 1999ae), however, NRC staff attributed DOE's inability to achieve this balance, in part, to the fact that some of the experts invited by DOE declined to participate as panel members – SER Vol. 3 page 20-5

- The final elicitation reports appropriately identified the participating subject matter experts, included summaries of their input to the elicitations, and provided rationales for their respective opinions (SER Vol. 3 page 20-6)

- DOE provided the expert panel the technical basis to support the elicitation consistent with guidance in NUREG-1563 based on NRC staff direct observation and review (SER Vol. 2—6)

**2) Probabilistic Seismic Hazard Assessment (PSHA)**

- DOE adequately documented the PSHA (CRWMS M&O 1998aa; BSC 2004bj) – SER Vol. 3 pages 20-3 and 20-8

- DOE's PSHA followed the standard framework for PSHAs in using the recurrence curve approach (e.g., Cornell, 1968aa; McGuire, 1976aa) – SER Vol. 3 page 20-3

- To accomplish the PSHA, DOE hired two panels of experts; the first expert panel consisted of six three-member teams of geologists and geophysicists (seismic source teams) who developed probabilistic distributions to characterize relevant potential seismic sources in the Yucca Mountain region and the second expert panel consisted of seven seismology experts (ground motion experts) who developed probabilistic point estimates of ground motion for a suite of earthquake magnitudes, distances, fault geometries, and faulting styles (the NRC staff considered that the experts possessed the necessary knowledge and expertise and that they collectively represented an appropriately broad spectrum of the larger seismology community – SER Vol. 3 page 20-6

- DOE provided the expert panel an adequate technical basis to support the elicitation consistent with guidance in NUREG-1563 based on NRC staff direct observation and review (SER Vol. 2—6)

3) **Saturated Zone Flow and Transport Expert Elicitation (SZEE)**

- DOE adequately documented the SZEE (CRWMS M&O 1998ab) – SER Vol. 3 pages 20-4 and 20-8

- To accomplish the SZEE a panel of five experts in saturated zone hydrology was asked to address 16 technical issues related to the study of saturated zone groundwater flow and radionuclide transport at Yucca Mountain (over a period of 6 months) - SER Vol. 3 page 20-4

- DOE provided the expert panel an adequate technical basis to support the elicitation consistent with guidance in NUREG-1563 based on NRC staff direct observation and review (SER Vol. 2—6)

## 20.4 References Specific to Expert Elicitation

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