CNWRA 2006-02
Revision 1

SUMMARY OF CURRENT UNDERSTANDING OF DRIFT DEGRADATION AND ITS EFFECTS ON PERFORMANCE AT A POTENTIAL YUCCA MOUNTAIN REPOSITORY

Prepared for

**U.S. Nuclear Regulatory Commission
Contract NRC–02–02–012**

Prepared by

**Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas**

**August 2006
Revised January 2007**

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August 2006
Revised January 2007

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EXECUTIVE SUMMARY

This report examines information regarding the degradation of emplacement drifts and the effects of drift degradation on long-term performance of a potential nuclear waste repository at Yucca Mountain, Nevada. The current U.S. Department of Energy (DOE) design of the underground facility considers cylindrical waste packages arranged horizontally in emplacement drifts and inverted U-shaped drip shields covering the waste packages. The drifts could degrade after permanent closure from the effects of thermal stress, seismic ground motion, or gradual weakening of rock around the openings. Independent analyses conducted by the Center for Nuclear Waste Repository Analyses (CNWRA) under U.S. Nuclear Regulatory Commission (NRC) guidance show that degradation of the emplacement drifts after permanent closure could affect the mechanical integrity of drip shields and waste packages. Thermohydrologic parameters important to corrosion and seepage could also be affected by drift degradation. These effects could be important to waste isolation, depending on the timing, rate, and extent of drift degradation.

Drift degradation may affect drip shields and waste packages through dynamic impact from falling rock blocks, loading from accumulated rubble, or the effects of rubble on thermohydrological parameters important to corrosion and seepage. DOE recognizes two types of rock at the repository site based on mechanical characteristics important to drift degradation: lithophysal rock, which occupies approximately 85 percent of the repository site area, and nonlithophysal rock, which occupies the remainder. According to DOE, mechanical behavior of the nonlithophysal rock would be controlled by movement on existing fractures, such that degradation of drifts in nonlithophysal rock could result in rock blocks large enough to damage a drip shield from the dynamic impact of falling rock. On the other hand, mechanical behavior of the lithophysal rock would be controlled by a combination of fractures and lithophysae (holes formed in the rock by trapped gas during the cooling of magma), such that blocks resulting from drift degradation would generally be too small to damage a drip shield from the dynamic impact of falling rock. Therefore, to assess potential effects of drift degradation, DOE considers the dynamic impact of falling rock in nonlithophysal rock areas and accumulated rubble in lithophysal rock areas. DOE also recognizes two sets of environmental conditions for drift degradation assessment: nominal conditions, which include the effects of repository excavation and thermal loading, and a seismic scenario, which considers the effects of low-probability seismic ground motion.

Five potential events related to drift degradation would be considered in the DOE scenario analysis. Four of the events would be excluded from the performance assessment model on the basis of low consequence, and one event would be included in the model. The excluded events relate to potential damage to drip shields or waste packages from rockfall (impact from falling rock) or rubble accumulations under nominal conditions or the seismic scenario. Rockfall under nominal or seismic-scenario conditions would be excluded from the DOE performance assessment model on the basis that the drip shield would be designed to withstand potential dynamic rock-block impact and, although it may sustain cracks as a result of such impact, the cracks would subsequently heal, eliminating a potential path for water ingress. Mechanical damage from rubble loadings also would be excluded from the DOE performance assessment model because (i) there would not be any significant rubble accumulations under nominal conditions and (ii) the drip shield would be designed to withstand loading from seismically induced rubble without sustaining damage. Current DOE analyses, however, include the effects of seismically induced rubble in the evaluation of thermohydrologic parameters used to assess seepage and corrosion.

Based on current staff[1] understanding, the DOE approach of accounting for the potential effects of drift degradation in its Total System Performance Assessment does not include a complete range of credible scenarios considering potential behavior of the emplacement drifts, drip shields, and waste packages. Independent analyses by CNWRA staff suggest (i) repository thermal loading (based on the current DOE design concept) could cause degradation of the emplacement drifts and significant accumulations of rock rubble and (ii) the drip shield, as currently designed, could collapse onto the waste package as a result of static or seismic loading from the accumulated rubble. Staff currently are evaluating the risk significance of these results using the NRC Total-system Performance Assessment code. The central concern, however, is that potentially significant failure modes of the drip shields and waste packages are not being appropriately considered by DOE in its current analyses. The staff would seek clarifications from DOE on related technical matters during future interactions.

[1]In this document, the word “staff,” except where qualified with CNWRA or NRC, refers to “CNWRA and NRC staff.”

ACKNOWLEDGMENTS

This report was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the U.S. Nuclear Regulatory Commission (NRC) under Contract No. NRC–02–02–012. The activities reported here were performed on behalf of the NRC Office of Nuclear Material Safety and Safeguards, Division of High-Level Waste Repository Safety. This report is an independent product of CNWRA and does not necessarily reflect the view or regulatory position of NRC. The NRC staff views expressed herein are preliminary and do not constitute a final judgment or determination of the matters addressed or of the acceptability of a license application for a geologic repository at Yucca Mountain.

The authors gratefully acknowledge the technical review of W. Patrick; programmatic review of S. Mohanty, B. Sagar, and NRC staff; and editorial review of L. Mulverhill. Appreciation is due to R. Mantooth for assistance in the preparation of this report.

QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: All CNWRA-generated original data contained in this report meet quality assurance requirements described in the Geosciences and Engineering Division Quality Assurance Manual. Sources of other data should be consulted for determining the level of quality of those data. FracMan® simulations of nonlithophysal rocks are documented in CNWRA scientific notebook 798E. System analyses reported in Section 6.2 are documented in CNWRA scientific notebooks 355 and 782E.

ANALYSES AND CODES: The following commercial off-the-shelf software packages were used for analysis: FracMan Version 2.6 (Golder Associates, Inc., 2002, 1998) and RockWare StereoStat® Version 1.3 (Rockware, Inc., 2004). All commercial off-the-shelf software packages used in this report are under Technical Operating Procedure (TOP)–018 control.

References:

Golder Associates, Inc. "FracWorksXP Module User Documentation." Seattle, Washington: Golder Associates, Inc. 2002.

Golder Associates, Inc. "FracMan Interactive Discrete Feature Data Analysis, Geometric Modeling, and Exploration Simulation User Documentation." Version 2.6. Seattle, Washington: Golder Associates, Inc. 1998.

Rockware, Inc. "StereoStat." Version 1.3. Golden, Colorado: Rockware, Inc. 2004.

1 INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) has published criteria in 10 CFR Part 63 governing the licensing of geologic disposal of high-level radioactive waste at Yucca Mountain, Nevada. The regulations in 10 CFR Part 63 require that a license application include an assessment of the features, events, and processes of the repository system expected to significantly affect compliance with the postclosure performance objectives and an assessment of the anticipated response of the repository system to the range of design thermal loadings under consideration.

Based on available information, the current U.S. Department of Energy (DOE) subsurface design consists of waste packages containing high-level radioactive waste emplaced in horizontal drifts. To assure safe operating conditions during preclosure, DOE recognizes the need for designing stable underground openings. To this end, DOE plans to provide stainless steel bolts and other reinforcements in its ground support design. However, these reinforcements are recognized to be effective for limited periods and are not relied on for providing long-term stability of emplacement drifts during the postclosure period. The main focus of this report is repository performance after permanent closure.

According to current information, DOE plans to install drip shields over the waste packages before permanent closure of the potential repository. Stresses resulting from excavation, heat generated by decay of the spent nuclear fuel, or seismic ground motions may affect the stability of rock surrounding the drift openings. Dynamic impacts of falling rock blocks and static or dynamic loading from accumulated rubble could potentially result in mechanical damage to drip shields and waste packages. Additionally, rubble accumulation and changes in drift geometry could alter the characteristics of the near-field environment enough to affect the performance of engineered barriers. Therefore, understanding the timing, rate, and extent of drift degradation is important to evaluating the significance of these processes to repository performance. Substantial uncertainties exist in estimates for the timing, rate, and extent of drift degradation, which arise from the complexity of the contributing processes and recognized limitations of the numerical models and analytical techniques used to evaluate these processes for long periods of time.

As currently presented in available documents, DOE analyses conclude that the emplacement drifts are expected to remain essentially stable for thousands of years, unless the site experiences strong seismic events. Therefore, DOE currently plans only to evaluate the effects of seismically induced drift degradation in its performance assessment supporting a potential license application. DOE considers that a structurally competent drip shield would minimize, or preclude, potential waste package damage due to falling rock or accumulated rubble.

After reviewing the current DOE information, the Center for Nuclear Waste Regulatory Analyses (CNWRA), under NRC guidance, has conducted focused, independent verification analyses to understand the likelihood and consequences of drift degradation resulting from thermally or seismically induced stresses. These analyses indicate the projected thermally induced stresses could cause degradation of the emplacement drifts. The addition of seismic stresses could potentially enhance the degradation process. The analyses also suggest that, compared to DOE calculations, degradation could be more extensive and the resulting loads on the engineered barriers potentially higher. The analyses further indicate that significant amounts of degradation could occur early in the postclosure period, making the timing of the degradation an important factor affecting engineered barrier performance.

CNWRA staff, under NRC staff guidance, conducted additional, focused analyses to investigate the ability of a drip shield, as currently designed by DOE, to support static or dynamic loading from accumulated rock rubble. These analyses consider a reasonable range of loading conditions and suggest that loading from accumulated rubble could result in mechanical damage to the drip shield. Damage of drip shields could lead to exposure of the waste packages to seepage moisture, resulting in potential localized corrosion of the waste packages. For some configurations, loads from the rubble could possibly be transferred to the waste packages and create the potential for adverse effects on performance. Staff[1] are factoring the insights gained from the independent analyses to review the information supplied by DOE and are focusing reviews on those aspects considered significant to repository performance.

Staff recommended closing the Repository Design and Thermal-Mechanical Effects key technical issue agreements related to drift degradation[2] and Container Life and Source Term key technical issue agreements related to mechanical performance of the drip shield[3] on the premise that DOE would demonstrate the integrity of the drip shield during the regulatory period. The same premise for issue closure applies to other agreements related to the effects of drift degradation on near-field processes. However, current information from DOE does not clearly demonstrate the integrity of a drip shield under loading conditions that could be reasonably expected during the regulatory period.

This report documents the current staff understanding of the DOE approach for assessing the likelihood and potential consequences of drift degradation on repository performance and summarizes the results of independent analyses. Chapter 2 discusses the current DOE disposition of features, events, and processes related to drift degradation and aspects of subsurface design potentially affecting repository performance after closure. Chapter 3 highlights site characterization information supporting the DOE drift degradation analysis. Chapter 4 discusses current DOE analyses supporting the assessment of the likelihood of drift degradation and summarizes staff concerns with this information. Chapter 5 discusses the current analyses supporting the DOE assessment of consequences resulting from drift degradation and summarizes staff concerns with this information. Chapter 6 highlights the implementation of included features, events, and processes related to drift degradation into the DOE performance assessment and summarizes a proposed abstraction to understand the possible consequences of drift degradation for an NRC independent performance assessment. Chapter 7 summarizes the staff understanding of the current DOE approach and staff concerns that should be discussed further with DOE.

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[1]In this document, the word "staff," except where qualified with CNWRA or NRC, refers to "CNWRA and NRC staff."
[2]Pre-licensing Evaluation of Agreements in "Technical Basis Document Number 4, Mechanical Degradation and Seismic Effects" and Three Other Associated Agreements. Letter, January 11: L.E. Kokajko (NRC) to J.D. Ziegler (DOE). 2005.
[3]Pre-licensing Evaluation of Container Life and Source Term Agreements CLST.1.14, 2.08 and 2.09 in Technical Basis Document Number 6, Waste Package and Drip Shield Corrosion." Letter, December 29: L.E. Kokajko (NRC) to J.D. Ziegler (DOE). 2004.

2 SIGNIFICANCE TO WASTE ISOLATION

The subsurface design for a potential Yucca Mountain repository may include emplacement drifts; access ramps, mains, and turnouts; ventilation intake and exhaust shafts; and other openings to support various activities such as ventilation and performance monitoring. The performance of underground openings through the preclosure period appears relevant to staff reviews of a potential license application in areas of, for example, performance confirmation, implementation of design assumptions used in performance assessment, and aspects of repository operations before permanent closure. Additionally, ground support elements used in the emplacement drifts (e.g., rock bolts) could potentially influence repository performance if rock-mass characteristics important to seepage are altered by the presence of the support elements.

The performance of emplacement drifts after permanent closure appears relevant to assessing repository performance because of potential effects of drift degradation on engineered barrier performance and thermohydrological parameters important to seepage and corrosion. The DOE waste emplacement design (DOE, 2004a,b) considers cylindrical waste packages arranged horizontally in emplacement drifts and inverted U-shaped drip shields covering the waste packages. Drift degradation could affect drip shields and waste packages through dynamic impact from falling rock blocks, loading from accumulated rubble, or the effects of rubble on thermohydrological parameters such as temperature and relative humidity. The DOE disposition of features, events, and processes related to drift degradation is summarized in this chapter based on currently available DOE information. The DOE disposition (i.e., screening arguments or model abstractions) of these and related (i.e., those arising as a consequence of drift degradation) features, events, and processes is evaluated in subsequent chapters.

2.1 Potential Impacts of Drift Degradation on Repository Waste Isolation Capabilities

DOE has identified the (i) unsaturated rock units overlying the repository and host unit, (ii) unsaturated rock below the repository, and (iii) saturated volcanic tuff and alluvial deposits below the water table as potential natural barriers to waste isolation (Bechtel SAIC Company, LLC, 2004a). The drip shield, waste package, cladding, waste forms, and invert have been identified as potential engineered barriers to waste isolation (Bechtel SAIC Company, LLC, 2004a) that may effectively isolate waste and limit releases to the accessible environment.

Degradation of emplacement drifts (Bechtel SAIC Company, LLC, 2004b) could potentially limit the capabilities of some of the barriers identified by DOE, including the unsaturated rock overlying the repository and host unit, drip shield, waste package, cladding, and waste forms. In the risk insights baseline (NRC, 2004), the NRC staff indicate that over time, mechanical loading from rubble accumulated from drift degradation may lead to degradation of the waste isolation capabilities (i.e., to reduce or limit the rate of water or radionuclides flow or to prevent the release or substantially reduce the release rate of radionuclides from the repository to the accessible environment). The reduction or loss of waste isolation capabilities for the engineered barriers will depend on the accumulation rate of rubble in the drift and the threshold load-bearing capacity of drip shields and waste packages. The accumulation rate of rubble is expected to be primarily dependent on thermally and seismically induced stresses. As discussed in subsequent sections, DOE analyses suggest that thermally induced stresses will minimally affect the waste isolation capabilities of the engineered barriers. CNWRA analyses suggest that potential mechanical breaching of the drip shield depends on the extent of drift collapse resulting from thermally induced stresses (Ibarra, et al., 2006). Thermal stresses are expected to be most significant during the first few thousands of years until the waste forms cool sufficiently. CNWRA analyses also suggest that mechanical interactions between a collapsed drip shield and waste package may not be sufficient to mechanically breach a waste package unless sufficient seismic stresses are induced (Ibarra, et al., 2006). Seismic events could amplify static loads by (i) rubble consolidation and (ii) dynamic effects from ground accelerations. The timing and magnitude of seismic events are highly uncertain. Based on the CNWRA analyses, however, waste package damage from seismically induced stresses is expected to be more important before the drip shield is fully corroded than afterward.

Accumulated rubble is also anticipated to increase the waste package and drip shield temperatures, which could adversely affect their load-bearing capacities and may also accelerate their corrosion through the possible formation of more aggressive chemistry as well as subsequent waste form dissolution. For instance, CNWRA analyses suggest that if seepage contacts the waste package during the thermal pulse (i.e., in the first few thousands of years) there is a nonnegligible probability that brines capable of inducing localized corrosion on the waste package could form, with welds more likely to be affected (Pensado, et al., 2006; Dunn, et al., 2005). However, the timing and extent of drift collapse are highly uncertain. Long-term persistence of localized corrosion in limited-volume solutions leading to waste package breaching is also uncertain.

In addition, the effects of potential mechanical interactions between the drip shield and waste package, the effects of drift degradation on water seepage into potentially degraded drifts, and the effects of elevated temperatures caused by accumulated rubble from drift degradation on material behavior such as creep are key areas in which uncertainties are identified in NUREG–1762 (NRC, 2004).

2.2 DOE Disposition of Features, Events, and Processes Related to Drift Degradation

DOE documents the identification and technical basis for inclusion or exclusion of features, events, and processes with respect to the degradation, deterioration, or alteration of engineered barriers in the performance assessment, including those processes that could adversely affect the performance of natural barriers over the first 10,000 years after permanent closure as a result of drift degradation (e.g., Bechtel SAIC Company, LLC, 2004c). Screening arguments consider degradation of both nonlithophysal and lithophysal rock units, resulting from thermal stresses combined with any time-dependent rock weakening or seismic events. The disposition of the features, events, and processes addresses potential effects of drift degradation on in-drift thermohydrology and the capabilities of engineered barriers to isolate waste (Bechtel SAIC Company, LLC, 2004c).

Five features, events, and processes directly related to drift degradation are titled (i) rockfall, (ii) drift collapse, (iii) seismically induced rockfall damages engineered barrier subsystem components, (iv) seismically induced drift collapse damages engineered barrier subsystem components, and (v) seismically induced drift collapse alters in-drift thermohydrology (Bechtel SAIC Company, LLC, 2004c). Only item (v) is included in the DOE Total System Performance Assessment model. The other four features, events, and processes are excluded on the basis of low consequence. In summary, DOE argues (Bechtel SAIC Company, LLC, 2004c) that the drip shield is structurally capable of withstanding any static rubble load or dynamic rock-block impact. Additional stresses induced on the drip shield from such loads may cause stress corrosion cracking, but the resulting microscopic cracks, according to the DOE argument, are expected to be tight and infilled with corrosion products and mineral deposits. Thus, DOE does not envision that the drip shield will contact the waste package or fail to protect the waste package from seepage as a result of the potential mechanical loading. The potential effects of drift degradation on thermohydrology [i.e., item (v)] are the only related features, events, and processes directly addressed through abstracted models in the DOE Total System Performance Assessment model. Features, events, and processes related to effects of drift degradation on engineered barrier system performance, mechanical behavior of the drip shield and waste package, and seepage and in-drift environment are discussed in Chapter 5. The screening arguments for the five features, events, and processes directly related to drift degradation are discussed in Bechtel SAIC Company, LLC (2004c) and summarized in the following paragraphs.

2.2.1 Rockfall

DOE indicates this potential event would be excluded from the Total System Performance Assessment model on the basis of low consequence (Bechtel SAIC Company, LLC, 2004c). Based on DOE information (Bechtel SAIC Company, LLC, 2004b), rockfall may result from gravitational forces and excavation-induced or thermal stresses; however, the extent of rockfall would be minimal, with a total rock volume ranging from a few cubic meters to approximately 39.4 m^3 [1,391.4 ft^3]. This latter value was estimated for the preclosure seismic case in nonlithophysal rock. The DOE screening argument for rockfall is that the drip shield is capable of withstanding dynamic impact from a 14.5-metric ton [3.2×10^4 lb] rock block without contacting the waste package and up to 11.5 metric tons [2.5×10^4 lb] if higher impact velocities are considered. DOE estimates the maximum rock loads on the drip shield would be far smaller than these limits (Bechtel SAIC Company, LLC, 2004c). DOE also indicates accumulated stresses from multiple rockfalls on the drip shield would not exceed the tensile strength of the drip shield material. Although sufficient stress levels may develop to support stress corrosion cracking under appropriate aqueous environments, DOE assumes the cracks would be plugged with corrosion products and mineral precipitates. This plugging is reportedly sufficient to prevent contact of seepage with the waste package.

In summary, the DOE basis for screening out rockfall consists of two parts. First, DOE expects the drip shield would withstand loading from potential dynamic rock-block impact. Second, although DOE expects stress buildup on the drip shield may be sufficient to support stress corrosion cracking, DOE indicates any cracks that develop would be plugged with corrosion products and mineral precipitates, effectively preventing seepage from contacting the waste package. Therefore, DOE concludes rockfall would not have sufficient consequence to merit inclusion in the Total System Performance Assessment model.

2.2.2 Drift Collapse

DOE excludes this potential event from the Total System Performance Assessment model on the basis of low consequence (Bechtel SAIC Company, LLC, 2004c). The screening argument is based on the drift degradation analysis report (Bechtel SAIC Company, LLC, 2004b), which indicates only minor degradation of emplacement drifts (including enlargement) would occur for the static (i.e., nonseismic) loading case. DOE suggests the net effect can be sustained by the drip shield; minor degradation would result in only minor and localized deviations from the thermal and hydrologic conditions calculated without drift degradation, and only minimal consequences to the engineered barrier system components could result (Bechtel SAIC Company, LLC, 2004c, p. 6-50).

2.2.3 Seismically Induced Rockfall Damages Engineered Barrier Subsystem Components

DOE indicates this potential event would be excluded from the Total System Performance Assessment model on the basis of low consequence (Bechtel SAIC Company, LLC, 2004c). To support the screening decision, DOE indicates that for drip shields located in the nonlithophysal zones (i) dynamic impact from large rock blocks could lead to stress buildup on the drip shield; (ii) the resulting stresses could be high enough to support stress corrosion cracking on the drip shield if the appropriate aqueous environments develop; and (iii) the resulting cracks are microscopic and are expected to be plugged with corrosion products and mineral precipitates, effectively preventing contact of seepage with the waste package. DOE also indicates that in the lithophysal zones, the host rock will produce only small fragments incapable of damaging the drip shield. DOE also argued that because adjacent drip shields do not separate during seismic events, the drip shields always would protect the waste package and its internals (e.g., cladding) from the effects of potential rockfall. Because rockfall is unlikely to cause drip shields to fail to protect the waste packages from seepage or contact with rocks, DOE argues, rockfall due to seismic events is excluded from the Total System Performance Assessment model.

2.2.4 Seismically Induced Drift Collapse Damages Engineered Barrier Subsystem Components

DOE plans to exclude this potential event from the Total System Performance Assessment model on the basis of low consequence (Bechtel SAIC Company, LLC, 2004c). DOE indicates that complete drift collapse is not predicted to occur in nonlithophysal zones for the peak ground velocities considered in the seismic scenario. Although drift collapse could occur in the lithophysal zones, DOE estimates the drip shield would withstand static loads from accumulated rubble with a drip shield safety factor of three. Because its analyses suggest either drift collapse is very unlikely (i.e., in the nonlithophysal zone) or the drip shield would withstand any static loads resulting from drift collapse where possible (i.e., in the lithophysal zones), DOE concluded that consequences of drift collapse did not merit inclusion in the Total System Performance Assessment model.

2.2.5 Seismically Induced Drift Collapse Alters In-Drift Thermohydrology

DOE proposes to include this potential event in the Total System Performance Assessment model (Bechtel SAIC Company, LLC, 2004c). The DOE model abstraction includes (i) changes in seepage induced by drift wall irregularities that reduce the effectiveness of the drift as a capillary barrier, (ii) changes in temperature due to the insulating effect of rubble on top of the drip shield, and (iii) potential secondary effects of temperature increases (e.g., higher waste form dissolution rates, higher susceptibility for localized corrosion of the waste package). DOE intends to account for seepage changes with increased values in uncertainty. In the lithophysal zones, seepage is assumed to be enhanced after seismic events. Also, seepage does not contact the waste package until the waste package temperature drops below 100 °C [212 °F].

The nonlithophysal zones are considered not significantly affected by seismic events, and it is assumed that seepage at the drift wall develops only after the wall temperature is below 100 °C [212 °F][1]. In the performance assessment model, lookup tables are used to estimate changes to the temperature, relative humidity, and seepage rate with respect to nominal values following seismic events. DOE indicates the lookup tables were developed from process-level modeling. If a seismic event occurs when conditions are appropriate for localized corrosion of the waste package, the performance assessment model assumes that all seepage contacting the drip shield also contacts the waste package. Once localized corrosion is initiated, diffusive transport away from the waste package is activated with a cross section equal to the waste package area directly exposed to seepage.

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[1]Aqueous environments needed to support corrosion processes could be sustained at above boiling temperatures by some deliquescent salts (present, for example, in dust) if enough moisture is available in air (Yang, 2006).

3 ENGINEERING GEOLOGY CHARACTERIZATION OF THE REPOSITORY SITE

This chapter examines DOE information characterizing the geology and mechanical behavior of the host rock for a Yucca Mountain repository. The information was developed through combinations of field mapping and testing, laboratory testing, and numerical modeling.

3.1 Geological Characterization

Bechtel SAIC Company, LLC (2004b) provides discussion and analysis of geological characteristics of lithophysal and nonlithophysal rock masses that are relevant to the engineering geology and mechanical analyses of drift stability and rockfall for the underground drift system at the potential Yucca Mountain site. Repository layout information (Bechtel SAIC Company, LLC, 2003a) is one of the direct inputs used in the drift degradation analysis (Bechtel SAIC Company, LLC, 2002, Figure 1-2, p. 1-4), and the EarthVision™ geologic framework model (Bechtel SAIC Company, LLC, 2002) is the primary source for the overall stratigraphic and structural information of the potential repository site. The average depth of the potential repository {300 m [984 ft] below the ground surface} is used in the drift degradation analyses along with the rock densities to calculate an initial, *in-situ* vertical (i.e., overburden) stress state. Stratigraphic variation in the potential repository host horizon is simplified in the DOE drift degradation analyses by treating only two broad categories of rock—lithophysal (approximately 85 percent of the repository area) and nonlithophysal (approximately 15 percent of the repository area).

Geometric fracture characteristics (i.e., orientation, intensity, size) are among the primary engineering characteristics of the rock mass important to geomechanical performance of the nonlithophysal rocks (Bechtel SAIC Company, LLC, 2004b). For the lithophysal rocks, fracture geometry, together with lithophysae abundance, are considered to be key controls on the behavior.

3.1.1 Fracture Characteristics

As part of the site characterization activities at Yucca Mountain, the DOE and its contractors have conducted fracture characterization studies on surface exposures and from the subsurface via boreholes and tunnels. In Bechtel SAIC Company, LLC (2004b), data from the Exploratory Studies Facility (Albin, et al., 1997; Eatman, et al., 1997; Barr, et al., 1996; Beason, et al., 1996) and Enhanced Characterization of the Repository Block Cross-Drift (Mongano, et al., 1999) serve as the primary sources for fracture geometry information. Fracture orientation, intensity, and size are the main geometric elements that are used in the DOE analyses of drift degradation.

Overall conclusions presented by DOE with regard to fractures include (i) the Topopah Spring Tuff is characterized by four orientation-based fracture sets; (ii) the abundance of large fractures {i.e., trace lengths greater than or equal to 1 m [3.3 ft]} is roughly inversely proportional to lithophysal abundance, such that nonwelded units have higher fracture intensities and few lithophysae (Bechtel SAIC Company, LLC, 2004b, Figure 6-5, p. 6-12); (iii) fractures have relatively short continuous trace lengths with ends that often terminate against other fractures or in solid rock (i.e., blind termination); (iv) relatively short trace lengths and nonpersistence lead to relatively few kinematically removable rock blocks in the Topopah Spring Tuff middle nonlithophysal zone; and (v) stability of the Topopah Spring Tuff lower lithophysal zone is controlled by short fractures {i.e., trace lengths less than 1 m [3.3 ft]} and lithophysae.

3.1.2 Lithophysal Abundance

Abundance and spatial distribution of lithophysal cavities are among the primary engineering characteristics affecting geomechanical performance of the lithophysal rocks (Bechtel SAIC Company, LLC, 2004b). The Topopah Spring Tuff upper lithophysal zone is characterized by small lithophysae {approximately 1–10 cm [0.4–4.0 in]} with a relatively uniform size distribution, whereas lithophysae in the lower lithophysal zone are more variable in size {<1 cm [0.4 in] to 1.8 m [5.9 ft]} and shape (e.g., spherical, elliptical, cuspate). The volume percentage of lithophysae vary consistently with stratigraphic position in both lithophysal zones (Bechtel SAIC Company, LLC, 2004b, Figure 6-5, p. 6-12).

DOE defined five rock mass categories based on the lithophysal porosity data (Bechtel SAIC Company, LLC, 2004b, Table 6-41, p. 6-152). DOE indicates lithophysal porosity correlates with mechanical properties, such that the lithophysal rock mass categories correlate with the mechanical-property categories as described in Section 3.2.2.4. The weakest rock (Category 1) has the highest lithophysal porosity (35 percent), whereas the strongest rock (Category 5) has the lowest lithophysal porosity (7 percent).

3.2 Mechanical Characterization

The DOE information characterizing the mechanical behavior of the repository host rock is described in Bechtel SAIC Company, LLC (2004b, Appendix E). For the nonlithophysal rock units, the information consists of the mechanical properties of intact rock and fracture surfaces and rock-mass properties based on correlations with empirical rock-quality indices. For the lithophysal rock units, the information consists of mechanical properties of the rock mass estimated based on laboratory testing of large-diameter specimens and numerical simulations. The mechanical properties of lithophysal rock are emphasized in this report because (i) a large fraction [approximately 0.85 based on Bechtel SAIC Company, LLC (2003a)] of the proposed length of emplacement drifts likely will intersect lithophysal rock and (ii) the assessment of drift degradation in nonlithophysal rock is influenced more by fracture geometry than by mechanical properties.

3.2.1 Mechanical Properties of Nonlithophysal Rocks

Mechanical properties information developed by DOE for the nonlithophysal rock units includes density, elastic parameters (Young’s modulus and Poisson’s ratio) and compressive strength parameters (unconfined compressive strength, friction angle, and cohesion) for intact rock, and rock mass strength and elastic modulus calculated from fracture data obtained in the Exploratory Studies Facility and the Enhanced Characterization of the Repository Block tunnels. The calculation of rock mass properties using the fracture data is described in Bechtel SAIC Company, LLC (2003b, pp. 8-127 through 8-143; 2004b, pp. E-45 through E-54).

3.2.2 Mechanical Properties of Lithophysal Rocks

The mechanical properties of the lithophysal rock units were developed from laboratory testing of large-diameter specimens and numerically simulated testing using micromechanics-based computer codes. The resulting information was used to develop relationships between the rock strength, defined in terms of the unconfined compressive strength, q_u , and stiffness, defined in terms of the Young's modulus, E . The q_u versus E relationship is important for assessing behavior under thermal loading because the rock-mass stiffness has a strong effect on thermal stress, whereas the rock-mass strength determines the load-bearing capacity (i.e., resistance to thermal stress) of the rock. The extent of thermally induced rockfall in a model calculation, therefore, is determined to a large extent by the prescribed relationship between rock strength and stiffness.

3.2.2.1 Determination of Rock-Mass Strength and Stiffness from Laboratory Testing

The DOE tested 29 cylindrical specimens of lithophysal rock under unconfined compression (Bechtel SAIC Company, LLC, 2004b, pp. E-22 through E-23). Six specimens from the Tptpll and 23 from the Tptpul units of the Topopah Spring Tuff were tested. The specimens had a diameter of approximately 292 mm [11.5 in]. Six specimens had a length-to-diameter (L/D) ratio of 1.5 or smaller, and the other 23 had a length-to-diameter ratio of 1.7–2.1. None of the specimens comply with the recommended L/D ratio of 2.5–3.0 (International Society for Rock Mechanics Commission on Testing Methods, 1981, p. 113). The measured strength of a specimen tends to increase as the L/D ratio decreases because of confinement at the specimen ends. An estimate by Obert, et al. (Jaeger and Cook, 1979, p. 144) indicates specimens with an L/D ratio of 2.0, 1.5, and 1.0 would give strength values of 1.025, 1.068, and 1.153, respectively, relative to the strength of a specimen of the same rock with L/D ratio of 2.5. This information suggests the potential error from using small L/D ratio increases as the ratio decreases. An empirical relationship from Obert, et al. (Jaeger and Cook, 1979, p. 144) could be used to correct errors from a small L/D ratio, but the correction could be misleading for an L/D ratio that is too different from the recommended values of 2.5–3.0. The CNWRA staff approach to evaluating the DOE test data (Bechtel SAIC Company, LLC, 2004b, pp. E-22 through E-23), therefore, may include disregarding results from specimens with a small L/D ratio. The DOE data (Bechtel SAIC Company, LLC, 2004b, table E-9, pp. E-22 through E-23), for example, includes test results from five specimens with an L/D ratio of 1.0, 1.1, 1.1, 1.2, and 1.3. The five specimens are so short relative to their diameter that their test conditions could have been substantially different from the assumed unconfined state.

3.2.2.2 Numerically Simulated Compression Testing of Large-Diameter Specimens of Lithophysal Rock

The DOE also numerically simulated compression testing of lithophysal rock specimens using the PFC2D computer code (Bechtel SAIC Company, LLC, 2004b, pp. E-33 through E-35). The modeled specimens were cylindrical with a diameter of 1 m [3.28 ft] and an L/D ratio of 1.0 or 2.0 (Bechtel SAIC Company, LLC, 2004b, p. 7-17). The analysis consisted of modeling lithophysal rock as an assemblage of bonded disk-shaped particles with a distribution of void spaces representing lithophysal openings. The shape, size, and spatial distribution of the openings were copied from a panel map of the Enhanced Characterization of the Repository Block cross drift (Bechtel SAIC Company, LLC, 2004b, Appendix O). Values of micromechanical parameters needed for the model (e.g., particle-contact shear and normal stiffness, bond shear and normal stiffness, and contact and bond shear strength) (Bechtel SAIC Company, LLC, 2004b, p. 7-18), were evaluated by calibrating the elastic stiffness and compressive strength of the model assemblage against the elastic stiffness and unconfined compressive strength of the rock determined from laboratory testing (Bechtel SAIC Company, LLC, 2004b, pp. 7-17 through 7-18). Several model calculations explored the effects of lithophysae shape, size, and volume fraction on q_u versus E relationships (Bechtel SAIC Company, LLC, 2004b, pp. E-31 through E-35).

The DOE micromechanical models were not calibrated against several rock-deformational processes that could affect the results. The tensile strength and dilation behavior (i.e., ratio of lateral to axial strains) of the model were not calibrated and may significantly affect the calculated results. DOE indicated the tensile and dilation behavior calculated using the models are generally reasonable based on previous experience. Although such qualitative judgment may be sufficient to indicate the general reasonableness of the modeling approach, a quantitative calibration against tensile strength, for example, is important because tensile failure at particle contacts appears critical to the behavior of rock under unconfined compression (cf., Bechtel SAIC Company, LLC, 2004b, p. E-33). Independent analysis (Cho, et al., 2004) indicates the basic formulation of a PFC2D micromechanical model (i.e., an assemblage of bonded discs calibrated against the elastic stiffness and unconfined compressive strength of the modeled rock) likely overestimates the tensile strength of rock and underestimates the potential dilation strain. Cho, et al. (2004) suggested model changes (e.g., use of assemblage of particle groups instead of individual particles) to improve the model response regarding tensile resistance and dilation straining. DOE appears to have used the basic formulation in its calculation, which would raise a concern regarding the calculated q_u versus E relationships.

The DOE information (Bechtel SAIC Company, LLC, 2004b, p. E-35) illustrates the q_u versus E relationship calculated from PFC2D modeling is generally steeper than the q_u versus E relationship derived from laboratory compression testing. The calculated information, therefore, could be misleading if used alone, but likely will be valuable in defining the positions of the upper- and lower-bound q_u versus E curves that could be derived from the laboratory data (e.g., Bechtel SAIC Company, LLC, 2004b, p. E-35).

3.2.2.3 Simulated Compression Testing of Large Panels of Lithophysal Rock with Material Variability

DOE also reported results from numerically simulated unconfined compression testing of rectangular specimens of lithophysal rock. The specimens, each 10 m by 5 m [32.8 ft by 16.4 ft], were intended to capture *in-situ* nonhomogeneity of mechanical properties more than was captured in each laboratory specimen. Each rectangular specimen was set up through random sampling of a statistically generated three-dimensional distribution of lithophysae volume fraction (Bechtel SAIC Company, LLC, 2004b, p. E-36 through E-37). A correlation developed by DOE (Bechtel SAIC Company, LLC, 2004b, p. E-34) was used to assign spatially variable Young's modulus and unconfined compressive strength as functions of lithophysae volume fraction within a rectangular specimen (Bechtel SAIC Company, LLC, 2004b, p. E-38). A numerically simulated unconfined compression testing of each specimen was performed using the UDEC computer code and a Voronoi-model representation of the mechanically heterogenous lithophysal rock (Bechtel SAIC Company, LLC, 2004b, pp. E-38 through E-42).

3.2.2.4 Summary of DOE Information Characterizing the Mechanical Behavior of Lithophysal Rocks

DOE used the combined information (laboratory data and two sets of calculations) to develop upper- and lower-bound q_u versus E relationships for lithophysal rock (Bechtel SAIC Company, LLC, 2004b, Figure E-18, p. E-42). DOE also used the combined results to divide the lithophysal rock into five mechanical-property categories (Bechtel SAIC Company, LLC, 2004b, Table E-11, p. E-39). DOE explained that the mechanical-property categories correlate with lithophysae volume fraction and used the correlation to calculate that rock-mass Categories 1 and 2 represent approximately 10 percent, Categories 3 and 4 represent approximately 60 percent, and Category 5 represents approximately 30 percent of the lower lithophysal unit (Bechtel SAIC Company, LLC, 2004b, pp. 6-151 through 6-152 and 6-163 through 6-164).

An independent analysis of the DOE laboratory q_u versus E data, excluding specimens with an L/D ratio smaller than 1.5, indicates that the values of q_u likely occur within the upper and lower limits defined as functions of E in Table 3-1 (Ofoegbu, et al., 2006, 2004). The limits defined in Table 3-1 compare well with upper- and lower-bound q_u values defined by DOE, except for a DOE interpretation that the lower-bound strength curve should be truncated at 10 MPa [1.45 ksi] (Bechtel SAIC Company, LLC, 2004b, Figure E-18, p. E-42). The values of q_u effective under conditions of sustained loading, such as expected from thermal loading of an emplacement drift, may be smaller than values suggested by the limits in Table 3-1 by a factor as small as 0.6, because testing under conventional laboratory loading rates typically overestimates the value of unconfined compressive strength (e.g., Lajtai and Schmidtke, 1986).

Table 3-1. Statistical Description of Unconfined Compressive Strength of Lithophysal Rock Units as a Function of Young's Modulus*

	Unconfined Compressive Strength (MPa)		
Young's Modulus (GPa)	Lower 95 Percent Confidence Limit	Mean	Upper 95 Percent Confidence Limit
5.0	4.8	13.5	21.5
10.0	7.9	19.1	29.6
15.0	11.1	24.7	37.7
20.0	14.2	30.3	45.8

*Based on data in Bechtel SAIC Company, LLC. "Drift Degradation Analysis." ANL–EBS–MD–000027. Rev 03. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2004.

4 DOE INFORMATION CHARACTERIZING DRIFT DEGRADATION AT A POTENTIAL YUCCA MOUNTAIN REPOSITORY

This chapter explains the meanings of drift degradation, rockfall, and drift collapse and examines DOE information for characterizing drift degradation at a potential Yucca Mountain repository. Information needed to characterize potential degradation of emplacement drifts includes the amount of rubble accumulations, shapes of degraded drift openings, sizes and shapes of rock blocks that may strike the engineered barrier components, and the rates of drift degradation. The importance of the information may vary depending on the rock mass characteristics and engineered barrier design. For example, the amount of accumulated rubble likely will be more important than the size and shape of rock blocks for the Yucca Mountain repository, because while rubble accumulations could develop in every emplacement drift, only a small fraction [15 percent or less based on DOE information (Bechtel SAIC Company, LLC, 2004b, p. 6-150)] of the drift length is expected to intersect a rock type that could generate individual rock blocks of appreciable size.

The DOE drift degradation information is discussed in Sections 4.2 and 4.3 along with information developed through independent analysis by CNWRA staff.

4.1 Definitions: Drift Degradation, Rockfall, and Drift Collapse

The existence of an underground opening, whether formed by artificial or natural excavation, changes stresses in the rock surrounding the opening. The nature and magnitude of these changes depend on the *in-situ* state of stress before the opening was created, geometry of the opening, and the mechanical properties of the rock. Stress changes around a long cylindrical opening in a homogenous, elastic, and isotropic rock mass of infinite extent, for example, can be described using the Kirsch solution (e.g., Goodman, 1980, p. 215). For this case, stress change varies with tangential position and radial distance relative to the axis of the opening but is independent of the elastic parameters for the rock. The rock stress around an underground opening could be modified further owing to seismic ground motions or a distribution of temperature change such as may result from a heat source located in the opening. In response, the rock would undergo different forms and magnitudes of deformation controlled by the rock mechanical properties and the nature and magnitudes of the stress change.

The current DOE design for a potential Yucca Mountain repository (DOE, 2004a,b) consists of horizontal arrays of parallel emplacement drifts with a center-to-center separation of 81 m [266 ft]. Each emplacement drift would be loaded with closely spaced waste packages to give a uniformly distributed thermal load. For a typical drift within an array, thermal expansion of the surrounding rock would be suppressed laterally, but a limited amount of vertically upward expansion can occur because of free movement at the ground surface. The induced thermal stress, therefore, would be greater in the horizontal direction (because of suppressed lateral expansion) and smaller in the vertical direction (because of relatively free upward vertical expansion). Rock surrounding the emplacement drifts, therefore, would tend to deform according to the styles illustrated in Figure 4-1 [i.e., a reverse-faulting style in the roof and floor areas of drifts and in the pillars and strike-slip or normal-faulting styles in the drift sidewalls (Ofoegbu, 2001)]. Additionally, rock close to the periphery of the drift openings would be subjected to tangential compression and may tend to buckle outward.

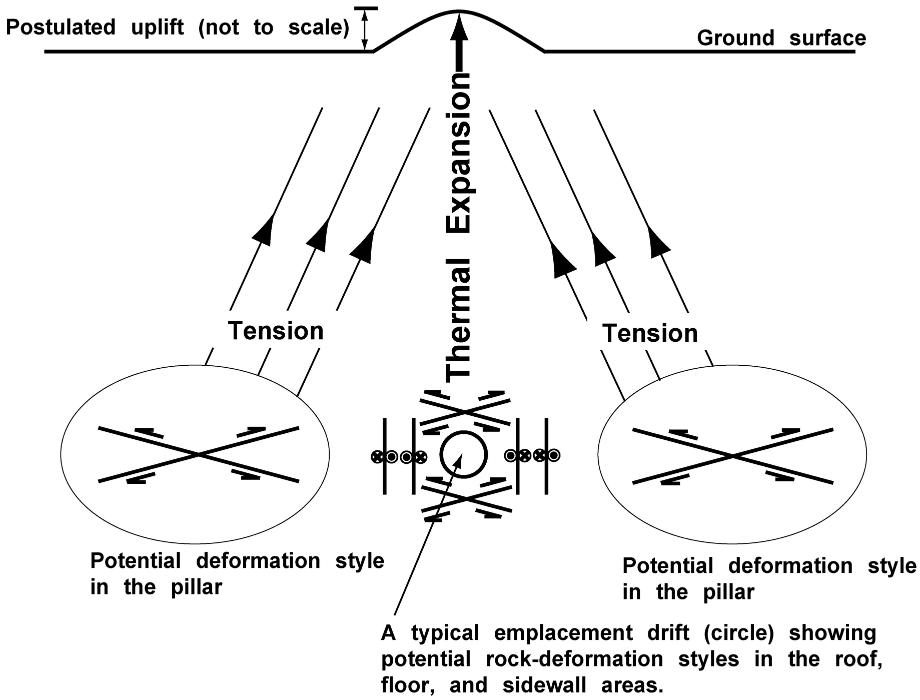

Figure 4-1. Postulated Styles of Thermally Induced Deformations Within an Array of Emplacement Drifts. The Induced Temperature Distribution and Rock Mechanical Properties Would Determine Actual Occurrence of the Postulated Deformations. (cf., Ofoegbu, 2001)

If the rock stress (thermally or seismically induced stress superimposed on the *in-situ* stresses modified by the excavation) exceeds the rock strength, then pieces of rock would break up following the aforementioned deformation styles. Broken rock pieces in the roof and sidewall areas would fall to the floor of the opening. The breakup and detachment of rock pieces from the wall of the opening and the accumulation of rubble in the opening result in a change in configuration of the emplacement drift. If the change in configuration is sufficient to affect any processes that are dependent on the geometry of the emplacement drift, then the drift is said to have degraded from its as-built configuration. The entire process of rock breakup and rockfall that leads to a change in emplacement-drift configuration sufficient to potentially affect processes dependent on the drift geometry is referred to in this report as drift degradation. The gravity-controlled or seismically aided fall of rock pieces from the roof or sidewall areas of the opening is referred to as rockfall. Drift collapse, as used in this report, represents an advanced stage of drift degradation when the underground space formed by the drift has been substantially occupied by rubble and substantial renovation would be needed to restore any necessary functionality of the drift.

The meaning of “rockfall” in DOE documents (e.g., Bechtel SAIC Company, LLC, 2004c, p. 6-46) is consistent with the definition provided in this report. DOE uses the term “drift collapse” to describe all stages of drift degradation, referring to early stages of drift degradation as “partial drift collapse” and the advanced stages as “complete drift collapse” (e.g., Bechtel SAIC Company, LLC, 2004c, p. 6-49). The terms “partial drift collapse” or “complete drift collapse” are not used in this report because both conditions are encompassed by the definition of drift degradation provided earlier. The term “drift collapse” may be used occasionally in this report to represent an advanced stage of drift degradation as defined earlier.

DOE information for characterizing potential drift degradation and rockfall at a Yucca Mountain repository is organized in terms of rock type (i.e., nonlithophysal or lithophysal rock) and postclosure scenario (i.e., nominal scenario or seismic scenario) (Bechtel SAIC Company, LLC, 2004b,c). Nominal-scenario conditions, according to DOE (Bechtel SAIC Company, LLC, 2004c, p. 6-47), include thermal loading, excavation- or gravity-induced stress, and any time-dependent weakening of rock. The DOE seismic scenario includes seismic ground motion with a mean annual probability of exceedance less than 5×10^{-4}. Therefore, any effects of a higher probability ground motion would be considered part of the nominal scenario.

4.2 Drift Degradation in Nonlithophysal Rocks

Degradation of emplacement drifts in nonlithophysal rock was characterized based on three-dimensional discrete-block model analyses of the rock mass (Bechtel SAIC Company, LLC, 2004b, p. 6-24 through 6-25 and 6-56 through 6-57). The models use fracture geometries obtained from a synthetic three-dimensional fracture-geometry distribution that DOE developed to represent the fracture population in a hypothetical block of the middle nonlithophysal unit of the Topopah Spring Tuff (Bechtel SAIC Company, LLC, 2004b, p. 6-26). The synthetic fracture distribution was stochastically generated using fracture data for nonlithophysal tuff at Yucca Mountain (Bechtel SAIC Company, LLC, 2004b, p. 6-27).

DOE used the analysis results to calculate the size, velocity, frequency, and total volume of rock blocks, as well as degraded-drift geometry that may result from seismically induced degradation of emplacement drifts in nonlithophysal rock (Bechtel SAIC Company, LLC, 2004b, p. 6-142). For drifts in nonlithophysal rock, the analyses indicate (i) thermally induced degradation would be negligible (Bechtel SAIC Company, LLC, 2004b, p. 6-102), (ii) change in drift geometry from seismically induced degradation would be negligible (Bechtel SAIC Company, LLC, 2004b, p. 6-142), and (iii) seismically induced rockfall may occur (Bechtel SAIC Company, LLC, 2004b, pp. 6-65 through 6-100). The DOE information is discussed in the following sections.

4.2.1 Approach to Drift Degradation Analysis in Nonlithophysal Rocks

As described in Section 3.1 of this report, DOE considers fracture geometry to be one of the key engineering characteristics of the rock mass affecting geomechanical performance of the nonlithophysal rocks. The DOE approach to assessing drift degradation in nonlithophysal Topopah Spring Tuff has three basic components: (i) data on natural fracture geometries at Yucca Mountain, (ii) stochastic fracture generation with FracMan (developed by Golder Associates, Inc.), and (iii) mechanical response analysis with 3DEC (developed by Itasca Consulting, Inc.) under thermal and seismic load conditions (Bechtel SAIC Company, LLC, 2004b, Section 3.1).

FracMan allows the user to stochastically generate synthetic fracture populations based on selected input criteria. Orientation, size (i.e., radius), and number of fractures (or an intensity measure) are the necessary geometric inputs for each fracture set and can be assigned constant values or distribution functions. For the drift degradation analysis of nonlithophysal rocks, DOE developed synthetic fracture populations for a hypothetical cubical block 100 m [328 ft] on a side. The input parameters for seven fracture sets (Bechtel SAIC Company, LLC, 2004b, Figure 6-18,

p. 6-34) were developed by DOE based on their analyses of large fractures (i.e., trace length >1 m [3.3 ft]) from the Topopah Spring Tuff middle nonlithophysal zone, excluding the intensely fractured zone (Exploratory Studies Facility stations 42 + 00 to 51 + 50). One subhorizontal set was generated along with six subvertical sets {i.e., three different mean orientations each with a subpopulation of long (trace lengths approximately 7 m [23 ft] or longer) and short (trace lengths approximately 7 m [23 ft] or shorter) fractures}. The overall synthetic fracture population was developed by sequentially generating sets based on the inferred timing of natural fracture formation. The subhorizontal fractures were generated first, followed by the long subvertical fractures, and finally the short subvertical fractures.

Discrete block modeling used the discontinuum code 3DEC, which treats the rock mass as a series of blocks separated by interface planes that represent rock fractures. The geometry of the interface planes was obtained by randomly sampling from the previously developed FracMan synthetic fracture population. The mechanical behavior of the interfaces was represented with a Coulomb slip criterion, and the blocks were treated as linear elastic (Bechtel SAIC Company, LLC, 2004b, Table 6-3, p. 6-61). DOE modified 3DEC to include representation of nonpersistent fractures because DOE has concluded that many of the fractures in the middle nonlithophysal unit terminate blindly in solid rock rather than abut other fractures. As such, the 3DEC models used for the DOE analysis included several rock bridges where portions of a fracture interface were assigned a bond strength equal to the strength of the rock blocks (Bechtel SAIC Company, LLC, 2004b, Figure H-1, p. H-2). The rock bridges essentially constrained the connected blocks from slipping or separating.

The discrete block model was embedded in a linear-elastic model to form a two-region drift-scale model. The drift-scale model consisted of a cube slightly larger than 25 m [82 ft] on a side with a 5.5 m [18 ft] diameter horizontal tunnel that trends 75° (Bechtel SAIC Company, LLC, 2004b, Figure 6-34, p. 6-60). The outer linear-elastic region consists of blocks bonded to prevent slipping or separating. The inner fractured-rock region surrounds the tunnel and extends to one tunnel diameter from the sides and two diameters above the roof. The drip shield was represented as a stiff, rectangular block fixed to the invert and served only to collect information on the locations and velocities of rockfall impact.

The initial stress conditions consisted of a vertical maximum principal stress of 7 MPa [1.02 ksi] and horizontal principal stresses of 3.5 MPa [0.51 ksi] oriented at 15° and 105°. Boundary conditions for the initial consolidation phase, excavation of the tunnel, and the thermal analyses consisted of zero displacement on the sides, top, and bottom of the block. For the dynamic (i.e., seismic) analyses, nonreflecting boundaries were used on the top and bottom and free-field boundaries on the sides of the block.

The DOE seismic loading conditions are based on site-specific ground motions (Bechtel SAIC Company, LLC, 2004b, Appendix X; Bechtel SAIC Company, LLC, 2004d) for five mean annual frequencies of exceedance: (i) preclosure ground motion (1×10^{-4} and 5×10^{-4}) and (ii) postclosure ground motion (1×10^{-5}, 1×10^{-6}, and 1×10^{-7}). For each postclosure hazard level, 15 sets of ground motions at the repository horizon were selected, and each set consists of two horizontal and one vertical component of displacement, velocity, and acceleration (e.g., Bechtel SAIC Company, LLC, 2004b, Figure 6-36, p. 6-67). Only one ground motion set was selected for each preclosure hazard level. The 3DEC rockfall analyses under seismic loading conditions consist of 50 combinations of one postclosure ground motion set with one fracture geometry extracted from the synthetic population (Bechtel SAIC Company, LLC, 2004b, Table 6-8, pp. 6-71 through 6-72).

Thermal loading used a sequential modeling approach. The temperature history was determined from two-dimensional NUFT thermohydrologic analyses for three different cases (Bechtel SAIC Company, LLC, 2004b, Figures 6-24 and 6-25, pp. 6-49 and 6-50). The temperature history was discretized into approximately 5 °C [41 °F] increments and used as input to FLAC, a computer code model, to calculate the corresponding thermally induced stress-state history around the emplacement drift (Bechtel SAIC Company, LLC, 2004b, Appendix U). The thermally induced stress history defined the loading conditions for the 3DEC rockfall analyses, which were conducted for three different fracture geometries. The fracture geometries were selected from the seismic loading analyses for a mean annual frequency of exceedance of 1×10^{-5}.

The DOE 3DEC analyses of rockfall in the nonlithophysal rocks under seismic loading conditions show that the number of blocks and the overall block volume and mass increase dramatically for the postclosure ground motion inputs compared to the preclosure motions (Bechtel SAIC Company, LLC, 2004b, Tables 6-26 and 6-27, p. 6-112 and Figure 6-81, p. 6-113). In the 3DEC analyses, fallen blocks were deleted once they struck the drip shield, so assessment of rubble accumulation was not explicitly conducted. Based on the thermal loading analyses, DOE concluded that thermal loading alone would produce only minor drift degradation (Bechtel SAIC Company, LLC, 2004b, Tables 6-21 and 6-22, p. 6-102). Finally, the 3DEC analyses indicate that rockfall induced by the combination of thermal and seismic loading would be less than that for seismic loading alone (Bechtel SAIC Company, LLC, 2004b, Tables 6-23 and 6-24, pp. 6-105 and 6-106).

DOE concluded that the input fracture pattern is the dominant control on the range of rockfall volume for a given ground motion level (Bechtel SAIC Company, LLC, 2004b). The effects of time-dependent rock joint strength degradation were assessed for three cases of ground motions with a mean annual frequency of exceedance of 1×10^{-5} by changing the input joint properties. The joint cohesion was reduced from 0.1 to 0.0 MPa and the joint friction angle was reduced from 41° to 30°. The primary effect of the changes to joint properties was a general increase in the number of rock blocks and the overall rockfall volume (Bechtel SAIC Company, LLC, 2004b, Table 6-25, p. 6-110).

4.2.2 Quantitative Characterization of Drift Degradation in Nonlithophysal Rock for Performance Assessment

Results from the analysis of drift degradation in nonlithophysal rock were used to estimate the size, velocity, and frequency of discrete rock blocks that may fall during a seismic event (Bechtel SAIC Company, LLC, 2004c, p. 6-23). The results also were used to estimate the potential rockfall volume (Bechtel SAIC Company, LLC, 2004c, p. 6-47) and change in emplacement-drift geometry (Bechtel SAIC Company, LLC, 2004c, p. 6-27) from potential degradation of emplacement drifts in nonlithophysal rock. For example, DOE used the analysis results to support a conclusion that seismic ground motions with a peak ground velocity smaller than 5.35 m/s [17.6 ft/s] would not cause collapse of emplacement drifts in nonlithophysal rock (Bechtel SAIC Company, LLC, 2004c, p. 6-27).

Staff are concerned that DOE likely underestimated potential seismically induced degradation of drifts in nonlithophysal rock because of the fracture geometry inputs used for the analyses.

Furthermore, the analysis did not include cumulative effects of multiple seismic events, and the assessment of model sensitivity was limited. These concerns are discussed in the following paragraphs.

Fracture data collected from the nonlithophysal rocks at Yucca Mountain serve as direct input to the DOE FracMan analyses, and the FracMan-generated synthetic fracture populations then form the primary geometric input to the 3DEC rockfall analyses. As Bechtel SAIC Company, LLC (2004b, p. 6-114) states, the fracture pattern is the predominant cause of variability in rockfall at a given level of peak ground velocity. Therefore, the fracture input to the FracMan simulations dominated the outcome of the rockfall analyses.

Staff have previously expressed concern (NRC, 2004; Virgilio, 2004) with the DOE representation of the Yucca Mountain fracture data in the FracMan analysis and indicated that a quantitative comparison of the DOE-generated FracMan synthetic fracture populations against the fracture data would be prudent. While the orientations of steeply dipping fractures in the synthetic population are similar to the natural fracture data, the shallowly dipping fracture set is underrepresented in the DOE synthetic population (Smart, et al., 2006). The DOE synthetic population also contains a concentration of moderately northeast-dipping fractures (Bechtel SAIC Company, LLC, 2004b, Figure 6-19, p. 6-38) that are not observed in the natural fracture population (Smart, et al., 2006, Figure 3-7, p. 3-17).

A synthesis of subsurface fracture data collected at Yucca Mountain demonstrates that the median spacing for low-angle fractures in the nonlithophysal rocks is less than the spacing for such fractures used in the DOE drift degradation analyses (Smart, et al., 2006, Table 5-1, p. 5-2). For the Topopah Spring Tuff middle nonlithophysal zone in particular, the spacing for low-angle fractures calculated from DOE data (Smart, et al., 2006, p. 5-2) is nearly five times smaller than the spacing used for the same fractures in the DOE analysis (Bechtel SAIC Company LLC, 2004b). To better understand the potential effect of this spacing difference, CNWRA staff performed independent simulations using FracMan (Golder Associates, Inc., 2002, 1998). Results suggest that the FracMan simulations based on the spacing calculated by Smart, et al. (2006) could lead to a greater number of low-angle fractures (Figure 4-2), which is readily observed on the vertical surfaces. As Table 4-1 shows, the fracture intensity calculated from the independent FracMan simulation by CNWRA staff matches the Yucca Mountain data more closely than the fracture intensity from a FracMan simulation based on the DOE inputs. The CNWRA staff analyses suggest that the total number of rock blocks that fall could be greater in the 3DEC simulations if a larger number of low-angle fractures was included. While the block size distribution was not specifically assessed by CNWRA analyses, the proportion of large blocks is expected to be smaller.

The DOE assertion that the nonlithophysal rock is dominated by nonpersistent fractures does not appear to be supported by the available fracture data. An independent review of the data (NRC, 2004, p. 18) suggests that the majority of the large scale fractures {i.e., trace lengths >1 m [3.3 ft]} abut or cut across other fractures on at least one end where visible (i.e., not obscured by engineered supports). The argument for nonpersistent fractures in the nonlithophysal rocks is further weakened if small scale fractures {i.e., trace lengths <1 m [3.3 ft]} are considered, because these may link larger fractures, thus increasing overall connectivity. Consequently, excessive use of rock bridges in the 3DEC analyses appears to have produced a

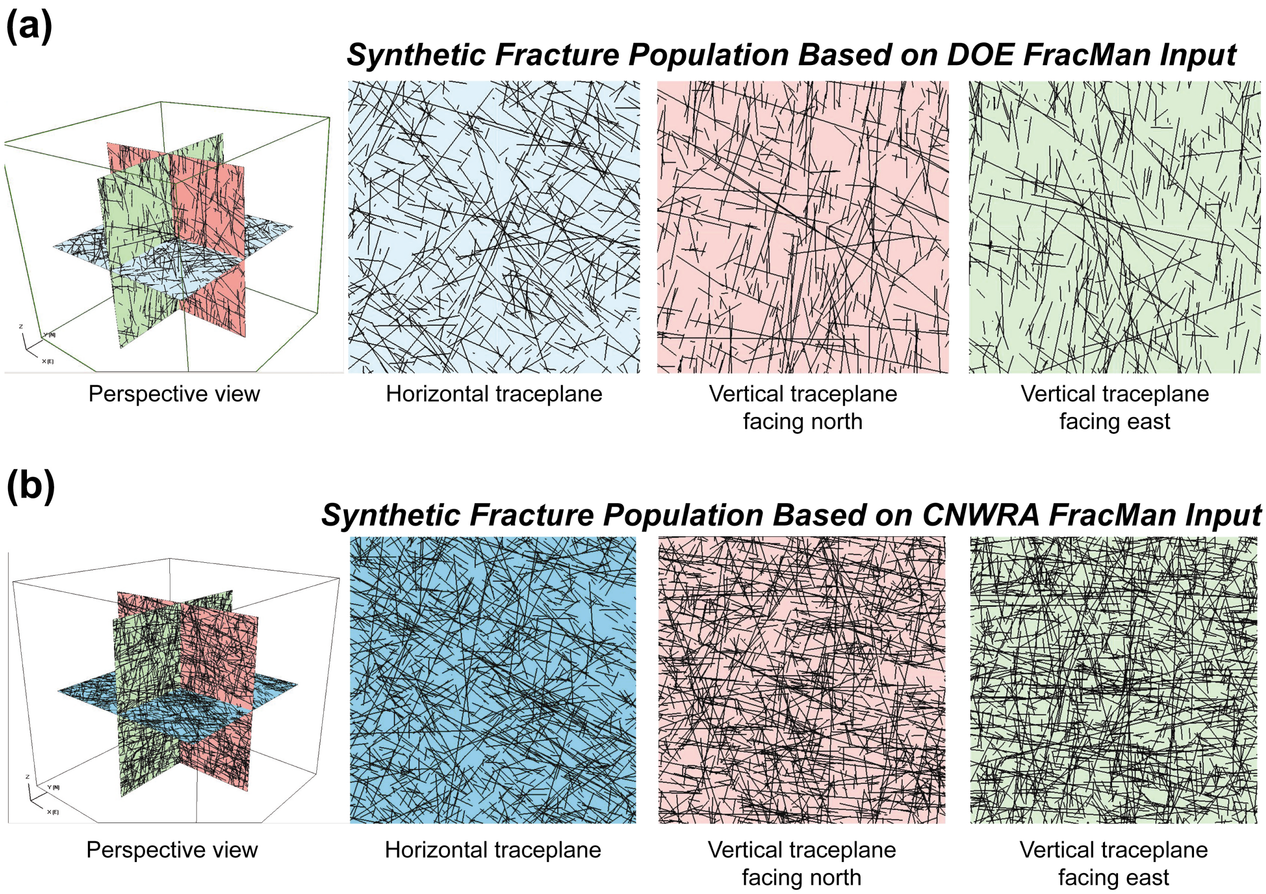

Figure 4-2. Comparison of FracMan Synthetic Fracture Populations Based on Input From (a) DOE (Bechtel SAIC Company, LLC, 2004b, Figure 6-18, p. 6-34) and (b) CNWRA (Smart, et al., 2006)

rock-mass model with fewer kinematically removable blocks than may be realistic for the nonlithophysal rock at Yucca Mountain. The DOE analysis would have resulted in greater rockfall volumes and larger changes in emplacement-drift geometry if a more accurate representation of fracture connectivity had been used.

The effect of time-dependent joint degradation was assessed for the case of 10^{-5} seismic ground motion (Bechtel SAIC Company, LLC, 2004b, Section 6.3.1.5). A degraded joint case was developed with the joint cohesion reduced from 0.1 to 0.0 MPa and the friction angle reduced from 41° to 30°. Results show that the total number of rock blocks increased (Bechtel SAIC Company, LLC, 2004b, Table 6-25, p. 6-110), but DOE concluded that the effect is minimal. Analyses for larger seismic ground motions (i.e., 10^{-6} and 10^{-7}) and thermal loading, however, were not presented in Bechtel SAIC Company, LLC (2004b).

Sensitivity analyses (Bechtel SAIC Company, LLC, 2004b, Section 6.3.1.6) assessed the effect of different joint mechanical properties on the number and volume of rockfall. Three joint

Table 4-1. Comparison of Linear Fracture Intensity (i.e., Number of Fractures Per Unit Length) for Fracture Sets in the Topopah Spring Tuff Middle Nonlithophysal Zone Based on Data From Yucca Mountain and FracMan Simulations Using DOE* and CNWRA† Input Values. Intensity for Synthetic Fracture Sets Was Determined From Average Value of Nine Boreholes Constructed Perpendicular to the Average Orientation of Each Set.

Fracture Set	Yucca Mountain	FracMan Synthetic Fractures	
		DOE	CNWRA
1	3.54 m^{-1} [1.08 ft^{-1}]	1.56 m^{-1} [0.48 ft^{-1}]	3.61 m^{-1} [1.10 ft^{-1}]
2	2.41 m^{-1} [0.73 ft^{-1}]	1.43 m^{-1} [0.44 ft^{-1}]	2.47 m^{-1} [0.75 ft^{-1}]
3	1.89 m^{-1} [0.58 ft^{-1}]	0.23 m^{-1} [0.07 ft^{-1}]	2.00 m^{-1} [0.61 ft^{-1}]

*Bechtel SAIC Company, LLC. "Drift Degradation Analysis." ANL–EBS–MD–000027. Rev 03. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2004.
†Smart, K.J., D.Y. Wyrick, P.S. Landis, and D.J. Waiting. "Summary and Analysis of Subsurface Fracture Data from the Topopah Spring Tuff Upper Lithophysal, Middle Nonlithophysal, Lower Lithophysal, and Lower Nonlithophysal Zones at Yucca Mountain, Nevada." CNWRA 2005-04. San Antonio, Texas: CNWRA. 2006.

property cases that explored variations in the friction and dilation angles and the normal and shear stiffness were developed (Bechtel SAIC Company, LLC, 2004b, Table 6-29, p. 6-116).

The sensitivity analyses were conducted for the case of 10^{-5} seismic ground motions only and suggest that the 3DEC rockfall results are generally insensitive to changes in joint mechanical properties. Analyses for larger seismic ground motions and thermal loading, however, were not presented in Bechtel SAIC Company, LLC (2004b).

The drift degradation analyses for the nonlithophysal rocks under seismic loading conditions did not include the effect of sequential earthquakes. In all cases presented in Bechtel SAIC Company, LLC (2004b), the analyses began from a pristine or undeformed state. Multiple 10^{-5} seismic events, however, could occur during the first 10,000 years after repository closure (Ibarra, et al., 2006, Table 5-2). Even if the first seismic event does not produce significant drift degradation, it could lead to a weakened state that might produce greater rockfall if subjected to a second seismic event (even if the followup event was smaller than the first) (Ahola, 1997; Ahola and Chowdhury, 1997; Ghosh, et al., 1995; Kana, et al., 1995).

4.3 Drift Degradation In Lithophysal Rocks

Based on its analysis, DOE concluded that (i) only minor degradation of emplacement drifts in lithophysal rock can be expected under nominal-scenario conditions for 10,000 years (Bechtel SAIC Company, LLC, 2004c, pp. 6-49 through 6-50); (ii) rockfall and rubble accumulations from drift degradation under nominal-scenario conditions would be too small to have any significant effect on repository performance (Bechtel SAIC Company, LLC, 2004c, p. 6-50); and (iii) collapse of drifts in lithophysal rock can be expected under seismic-scenario conditions, but the amount of rubble accumulation would not be sufficient to damage the engineered barrier components, such as a drip shield (Bechtel SAIC Company, LLC, 2004c, pp. 6-24 through 6-25).

The DOE conclusion regarding drift degradation under nominal-scenario conditions is based on an analysis of the mechanical effects of thermal loading on emplacement drifts in lithophysal rock (Bechtel SAIC Company, LLC, 2004b, pp. 6-180 through 6-183), which indicates drift degradation in lithophysal rocks from the effects of thermal loading and time-dependent rock weakening would be minor and therefore negligible in terms of performance. A DOE attempt to validate the rock-mass model used for the analysis, however, indicates potential thermally induced drift degradation may have been underestimated. Furthermore, independent analysis performed by CNWRA staff (Ofoegbu, et al., 2006) indicates potential degradation of emplacement drifts under the same conditions used in the DOE analysis. The DOE conclusion regarding seismically induced drift degradation in lithophysal rock is based on analysis of the effects of seismic ground motions on drift stability in lithophysal rock areas (Bechtel SAIC Company, LLC, 2004b, pp. 6-163 through 6-178). The analysis indicates occurrence of drift collapse under low-probability seismic ground motions, but comparison of the results with information from the literature (e.g., Kana, et al., 1991) suggests DOE may have overestimated the magnitude of seismic ground motion needed to initiate drift degradation. Also, DOE appears to have underestimated the amount of rubble accumulations owing to seismic events and the magnitudes of static load that could be transmitted to a drip shield through rubble accumulations. The DOE information regarding drift degradation in lithophysal rock is discussed in the following sections.

4.3.1 DOE Information Regarding Thermally Induced Drift Degradation in Lithophysal Rocks

Characterization of potential thermally induced degradation of emplacement drifts is based on thermal-mechanical analysis in which the rock mass was modeled as an assemblage of polygonal blocks (Bechtel SAIC Company, LLC, 2004b, pp. 6-153 through 6-156 and 7-33 through 7-40). The individual blocks can deform elastically, slide on or separate at the contacts with neighboring blocks, and detach from the assemblage and fall under the influence of gravity or seismically induced force. Therefore, the model could simulate rock deformation, stress, fracturing, breakage, or free fall of broken rock blocks (Bechtel SAIC Company, LLC, 2004b, pp. 6-153 through 6-156). Model behavior is controlled by block size, block elastic parameters (Young's modulus and Poisson's ratio), contact elastic parameters (shear and normal stiffness), and contact strength parameters (tensile strength, cohesion, and friction coefficient). Values of the model parameters were set by calibrating the unconfined compressive strength and elastic stiffness of the model (i.e., block assemblage) against the unconfined compressive strength and elastic stiffness of the modeled rock determined from laboratory test data (Bechtel SAIC Company, LLC, 2004b, pp. 7-33 through 7-40). The model is referred to in this report as the UDEC-Voronoi model, having been developed using Voronoi polygons and implemented in the two-dimensional distinct element computer code UDEC (Bechtel SAIC Company, LLC, 2004b, p. 3-1).

Properties of the model assemblage that may influence the calculated behavior but were not calibrated include tensile strength and stress-strain relationships under confined compression or in the postpeak phase of unconfined compression. The model is said to provide reasonable tensile strength and stress-strain relationships (Bechtel SAIC Company, LLC, 2004b, pp. 7-34 through 7-40), but calculated tensile strength or stress-strain relationships were not compared to measured data. Only the unconfined compressive strength and elastic stiffness of the model under unconfined compression were calibrated against measured data.

The DOE UDEC-Voronoi model was embedded in a two-dimensional linear-elastic model to obtain a drift-scale model for thermal-mechanical analysis (Bechtel SAIC Company, LLC, 2004b, Figure 6-116, p. 6-156). Temperature distributions calculated from a separate thermal-hydrological model were input to the drift-scale thermal-mechanical model to calculate the mechanical response of the rock mass to a prescribed drift thermal loading (Bechtel SAIC Company, LLC, 2004b, p. 6-180). A linearized drift thermal load of 1.45 kW/m [0.42 BTU/s/ft] with the time-decay characteristics illustrated in Bechtel SAIC Company, LLC. (2004b, Figure 6-24, p. 6-49) was used for the thermal-hydrological (therefore thermal-mechanical) model. Ten percent of the thermal load was applied during the first 50 years, and 100 percent was applied thereafter. The reduced thermal load during the first 50 years was based on a DOE thermal-load design specification that includes using forced ventilation to remove 90 percent of the waste-generated heat during the first 50 years after waste emplacement (Bechtel SAIC Company, LLC, 2004b, p. 5-1).

The DOE thermal-mechanical analysis used average values of Young's modulus and unconfined compressive strength for each of the five mechanical-property categories of lithophysal rock (Bechtel SAIC Company, LLC, 2004b, p. 6-182 and Table E-11, p. E-39). DOE also performed analysis to assess the effects of time-dependent weakening of the rock over 10,000 years (Bechtel SAIC Company, LLC, 2004b, Appendix S) using data from the literature on the delayed failure of a granitic rock (e.g., Lajtai and Schmidtke, 1986). Results of the DOE calculations representing the effects of thermal load alone (Bechtel SAIC Company, LLC, 2004b, Figure 6-140, p. 6-183) and the effects of thermal load superimposed on time-dependent rock weakening (Bechtel SAIC Company, LLC, 2004b, Figure S-42 through S-44, pp. S-45 through S-47) indicate no significant degradation of the emplacement drifts from these effects for 10,000 years. Results from the analysis of thermal load superimposed on time-dependent rock weakening indicate small accumulations of rubble, which DOE concluded would be too small to significantly affect repository performance (Bechtel SAIC Company, LLC, 2004c, p. 6-50).

DOE information also includes the results of a thermal-mechanical analysis performed to validate the UDEC-Voronoi model against measurements and observations from a drift-scale heater test performed by DOE (Bechtel SAIC Company, LLC, 2004b, p. 7-45 through 7-57). The UDEC-Voronoi model used for the validation analysis was calibrated to an unconfined compressive strength of 50–70 MPa and a Young's modulus of 30 GPa, which DOE indicated are appropriate for the rock mass at the location of the drift-scale heater test (Bechtel SAIC Company, LLC, 2004b, pp. 7-48 through 7-50).

Validation of the UDEC-Voronoi model is necessary because the coupled analysis of rock deformation, stress, fracturing, breakage, and free fall of broken rock, which the model was set up to accomplish, is unprecedented. In continuum modeling (e.g., Ofoegbu, et al., 2006), a coupled analysis of rock deformation and stress is performed, and the results are interpreted to infer potential fracturing, breakage, and rockfall. In discrete-block modeling, such as performed using the distinct element code UDEC (e.g., Itasca Consulting Group, Inc., 2004), a preexisting fracture population with characterized geometry and mechanical properties is specified to perform a coupled analysis of rock deformation, stress, slip or separation of existing fractures, and block fall. The continuum or discrete-block modeling techniques have been used previously, and the results calculated using these techniques generally are verifiable against previous work. The UDEC-Voronoi model represents an advancing of the state of the art in rock-mechanical modeling because it attempts to simulate rock fracturing and breakage without prespecified or characterized fracture geometry or mechanical properties. Consequently, model validation is necessary. The drift-scale heater test results provided appropriate information for such a validation.

DOE information (Bechtel SAIC Company, LLC, 2004b, p. 7-45) indicates rock spallation occurred in the roof area of the test drift between late 1999 and early 2001. Rubble accumulations caused the wire mesh (a component of the ground support system) to bulge downward (Bechtel SAIC Company, LLC, 2004b, Figure 7-29, p. 7-49). The wire mesh effectively held up the rubble and probably developed sufficient confinement to terminate the spallation. It is possible spallation would have progressed further if the wire mesh was not effective. In contrast, the DOE validation analysis does not show appreciable spallation or rubble accumulation (Bechtel SAIC Company, LLC, 2004b, Figure 7-31 through 7-36, pp. 7-52 through 7-57). The model used for the validation analysis did not include a wire-mesh ground support, which implies the model calculation should have shown at least the same amount of spallation and rubble accumulation observed in the actual test. The figures provided by DOE (Bechtel SAIC Company, LLC, 2004b, pp. 7-55 through 7-56) to illustrate that "large-scale" spallation (Bechtel SAIC Company, LLC, 2004b, p. 7-51) was calculated from the validation analysis show only a few blocks fell on the simulated drift floor. If the DOE validation analysis had been used to predict drift degradation for the drift-scale test, the extent of spallation and amount of rubble observed in the actual test (Bechtel SAIC Company, LLC, 2004b, Figure 7-29, p. 7-49) would not have been expected based on the results calculated from the validation analysis (Bechtel SAIC Company, LLC, 2004b, Figure 7-34, p. 7-55). Although there are safety implications, removing the wire-mesh ground support (the field test was stopped in April 2006) would enable DOE to document the amount of rubble accumulation from the field test. A comparison of the model calculation against the actual rubble accumulation may help determine how best to interpret results calculated using the UDEC-Voronoi model. The comparison provided by DOE (Bechtel SAIC Company, LLC, 2004b, pp. 7-45 through 7-57) suggests the extent of thermally induced drift degradation, and resulting calculated rubble accumulations may need to be increased to represent potential drift degradation and rubble accumulation in an emplacement drift.

4.3.2 Independent Analyses of Thermally Induced Drift Degradation in Lithophysal Rocks

Independent analysis by CNWRA (Ofoegbu, et al., 2006, 2004) indicates thermal- and excavation-induced stresses could cause persistent overstress of rock around an emplacement drift [considering the current DOE design (DOE, 2004)] for several hundred years after waste emplacement. The CNWRA staff explained the overstress would not cause instability if the openings were protected with adequate ground support, but interpreted the results to imply potential occurrence of progressive drift degradation and rockfall after any installed ground support degrades from corrosion, overstress, or other factors. A similar third-party analysis (Kemeny, et al., 2006) also indicated over stressed rock around the emplacement drifts, but the authors of the analysis did not infer any progressive drift degradation from the calculated overstress.

4.3.2.1 CNWRA Staff Analysis

The CNWRA analysis used a two-dimensional, drift scale, finite element model in which the lithophysal rock was modeled as a linear-elastic continuum with values of elastic parameters based on DOE information (as described in Section 3.2). The model geometry and thermal loading (including a thermal-load reduction credited to ventilation) also were based on DOE information (Bechtel SAIC Company, LLC, 2004b). The calculated rock stress was compared with the rock strength (described in Section 3.2) to determine potential overstress conditions.

The analysis indicates overstress conditions would be less likely during the ventilation period (except in the sidewall of drifts in low-grade lithophysal rock zones), but more likely after ventilation is terminated. For drifts in low-grade lithophysal rock zones, overstress would be more likely in the sidewall, but less likely in the roof. For drifts in high-grade lithophysal rock, in contrast, overstress would be more likely in the roof, but less likely in the sidewall. The initial over stressed zone may be up to a few meters thick in low-grade lithophysal rock areas, but only on the order of centimeters in high-grade lithophysal rock based on these results. The drifts would likely remain stable if the over stressed rock is held in place, such as with an effective ground support. If the overstress persists until any ground-support system becomes ineffective, the over stressed rock near the roof areas would break up and fall, unless the overstress is relieved by some other mechanism. The rockfall would expose new surfaces, which, if the heat flux from waste packages remained high enough, also would experience overstress, break up, and fall. Therefore, Ofoegbu, et al. (2006, 2004) interpreted the occurrence of thermally induced overstress in the roof area to imply potential occurrence of progressive drift degradation through thermally induced spallation. Overstress in the floor areas would cause the rock to break up, unless the overstress is relieved by a different mechanism. Rock breakup in the floor could cause the floor to buckle, but progressive failure of the underlying rock is not expected because any broken rock in the floor would remain in place, providing confinement that would likely end the failure process. Ofoegbu, et al. (2006, 2004) interpreted the occurrence of thermally induced overstress in the sidewall to imply potential progressive spallation of the sidewall area. Such spallation may ultimately increase roof instability. The analysis indicates overstress conditions occurring for at least 1,000 years after waste emplacement, based on the thermal load and material properties used in the thermal-mechanical model (Ofoegbu, et al., 2006).

4.3.2.2 Other Published Analysis

Kemeny, et al. (2006) provide overstress calculations for emplacement drifts using rock stress reported by DOE (Bechtel SAIC Company, LLC, 2004b). Overstress was determined in the analysis by comparing the rock stress with the lithophysal rock strength based on DOE information (described in Section 3.2). The analysis indicates a depth of over stressed rock of approximately 0.2–0.5 m [0.7–1.6 ft] from the drift perimeter. Kemeny, et al. (2006) did not infer any progressive drift degradation from the results, but instead concluded that any thermally induced degradation of the emplacement drifts would be limited to a skin around the opening and would not affect repository performance.

Kemeny, et al. (2006) did not provide any mechanism, however, to explain how degradation would terminate with the first skin of over stressed rock. For the degradation to terminate as postulated by Kemeny, et al. (2006), either the skin of over stressed rock would remain in place and protect the remaining rock mass from adverse stress conditions, or the source of overstress (i.e., drift thermal loading) would diminish before failure of the first skin of over stressed rock and overstressing of a subsequent skin. Kemeny, et al. (2006) did not provide a basis for mitigating conditions, but simply stated that the skin of over stressed rock calculated in their analysis represents the maximum extent of drift degradation.

4.3.3 DOE Information Regarding Seismically Induced Drift Degradation in Lithophysal Rocks

DOE characterization of potential degradation of drifts in lithophysal rock from seismic ground motions (Bechtel SAIC Company, LLC, 2004b, pp. 6-150 through 6-180) is based on UDEC-Voronoi modeling, as described in Section 4.3.1 of this report. The effects of seismic ground motions at mean annual frequency of exceedance of 10^{-5} and 10^{-6} were examined in the analysis (Bechtel SAIC Company, LLC, 2004b, pp. 6-155 through 6-156) using 15 ground motion time histories for each mean annual frequency of exceedance. The ground motion time histories represent varying spectral shapes, event durations, and peak ground motion magnitudes. The peak ground velocity varied from about 50–398 cm/s [20–157 in/s] and 78–817 cm/s [31–322 in/s] for the 10^{-5} and 10^{-6} ground motions, respectively (Bechtel SAIC Company, LLC, 2004b, Appendix X). DOE also performed analysis with one ground motion at a mean annual frequency of exceedance of 10^{-4}.

DOE examined the effects of varying the rock mechanical properties between limits defined in terms of the lithophysal rock categories (described in Section 3.2.2.4). For ground motions at a mean annual frequency of exceedance of 10^{-5}, DOE performed analysis using (i) mean strength of lithophysal rock categories 1, 3, and 5 and three ground motion time histories; (ii) lower-bound strength of lithophysal rock category 5 and three ground motion time histories; and (iii) a model with spatially variable mechanical properties and 15 ground motion time histories. For ground motions at a mean annual frequency of exceedance of 10^{-6}, DOE used the mean strength of lithophysal rock categories 1, 3, 4, and 5 in 15 random combinations with different ground motion time histories.

DOE indicates the results of the analysis lead to the following conclusions.

- Seismic ground motions at a mean annual frequency of exceedance of 10^{-6} or less would cause complete collapse of emplacement drifts irrespective of the lithophysal rock category (Bechtel SAIC Company, LLC, 2004b, p. 6-172).

- Seismic ground motions at a mean annual frequency of exceedance of 10^{-5} would cause varying amounts of drift degradation if the peak ground velocity is at least 100 cm/s [39.4 in/s] (Bechtel SAIC Company, LLC, 2004b, p. 6-170). The DOE information includes estimates of the amount of accumulated rubble as a function of peak ground velocity and lithophysal rock category (Bechtel SAIC Company, LLC, 2004b, Figure 6-128, p. 6-168).

- Seismic ground motions at a mean annual frequency of exceedance of 10^{-4} would not cause degradation of emplacement drifts in lithophysal rock (Bechtel SAIC Company, LLC, 2004b, p. 6-160).

The DOE conclusion that a minimum ground velocity of 100 cm/s [39.4 in/s] is needed to cause drift degradation appears inconsistent with the strength data for lithophysal rock available from DOE. The values of unconfined compressive strength of 10–30 MPa [1.45–4.35 ksi] (Bechtel SAIC Company, LLC, 2004b, Table 6-41, p. 6-152) suggest a tensile strength of 1–3 MPa [0.145–0.435 ksi], which can be used to estimate the minimum particle velocity that would cause tensile failure near the drift wall (cf., Bechtel SAIC Company, LLC, 2004b, Eq. 6-7, p. 6-158) to be approximately 20 cm/s [7.9 in/s]. Such ground motions would cause damage, such as slabbing, at the drift wall. Based on a review of empirical data on the response of mining and civil underground openings to seismic ground motions, Kana, et al. (1991) indicated a particle velocity of 20 cm/s [7.9 in/s] or greater could damage underground openings. The data reviewed by Kana, et al. (1991) include (i) a compilation by Owen and Scholl (1981), which indicates a minimum particle velocity of 50 cm/s [19.7 in/s] for underground-opening damage from earthquakes; (ii) information from Wagner (in Kana, et al., 1991), which indicates damage to mine openings from a particle velocity of approximately 26 cm/s [10.2 in/s] from mining-induced seismicity; and (iii) mining-induced seismicity information from Lenhardt (in Kana, et al., 1991), which indicates a minimum velocity of 30 cm/s [11.8 in/s] for rockfall and a minimum of 60 cm/s [23.6 in/s] for severe damage including fracture of intact rock.

Each of these sources of information, including a hand calculation based on DOE data as described earlier, suggests the minimum particle velocity needed to cause degradation of emplacement drifts in lithophysal rock likely is smaller than the 100 cm/s [39.4 in/s] estimated by DOE. Therefore, an alternative technique that is consistent with the existing data and current scientific understanding could result in greater seismically induced drift degradation and rubble accumulations than DOE estimated using the UDEC-Voronoi model.

4.3.4 Quantitative Characterization of Drift Degradation in Lithophysal Rocks for Performance Assessment

To quantify drift degradation in lithophysal rock to evaluate the potential effects on repository performance, the following are needed: (i) the drift configuration and rubble accumulation to estimate the temperature of the engineered barrier components and the quantities of water that may contact the components and (ii) potential mechanical loading from rubble to assess the mechanical performance of the engineered barrier components.

DOE has indicated its nominal-scenario analysis for performance assessment would not include a degraded-drift configuration because any drift degradation under nominal-scenario conditions would be too small to significantly affect repository performance (Bechtel SAIC Company, LLC, 2004c, p. 6-50). Therefore, DOE likely will use the as-built drift configuration for its nominal-scenario analysis. For the seismic scenario, DOE indicated mechanical loading from rubble need not be included in assessing potential effects of seismic ground motions because the drip shield would withstand potential rubble loads without buckling or collapse; therefore, it would protect the waste package from such loads (Bechtel SAIC Company, LLC, 2004c, p. 6-25). The drift and rubble configurations and rubble loading that DOE used to assess the mechanical performance of the drip shield were taken directly from results of the UDEC-Voronoi model calculations (Bechtel SAIC Company, LLC, 2004b, pp. 6-225 through 6-233). The DOE evaluation of the effects of drift degradation on seepage and temperature also were based on degraded-drift configurations calculated directly from UDEC-Voronoi modeling (Bechtel SAIC Company, LLC, 2004b, Appendix R; 2004c, pp. 6-26 through 6-28).

To assess the DOE approach for representing potential effects of drift degradation in performance assessment, this quantitative information is needed: (i) the degraded-drift geometry, amount of rubble accumulations, and mechanical loading of a drip shield owing to rubble accumulations and (ii) the rate of rubble accumulation. These two items are discussed in the following sections.

4.3.4.1 Degraded-Drift Configuration, Amount of Rubble Accumulations, and Associated Mechanical Loading

DOE information includes two sets of estimates of the amount of accumulated rubble and drip-shield static loading from rubble accumulations. One set was taken directly from results of the UDEC-Voronoi modeling (Bechtel SAIC Company, LLC, 2004b, pp. 6-225 through 6-233), and the other set was calculated using an analytical abstraction based on constraining the degraded-drift volume to satisfy a mass-balance principle (Bechtel SAIC Company, LLC, 2004b, pp. 6-217 through 6-220). DOE argued the estimates from UDEC-Voronoi modeling are more reliable than the estimates from the analytical approach, based on three assertions (Bechtel SAIC Company, LLC, 2004b, p. 6-232). First, the analytical model needs a user-specified shape for the degraded drift. The shape of the degraded drift, on the other hand, need not be specified in, but could be calculated from, the UDEC-Voronoi model. Second, the analytical model includes an assumption of full-load transmission through rubble. That is, frictional mechanisms (at times referred to as arching) that may reduce the amount of rubble weight transferred downward to a structure such as the drip shield are not included in the analytical model. The UDEC-Voronoi model, on the other hand, is formulated to include interparticle frictional interaction such that any load reductions from friction would be automatically included in the calculation. Third, the analytical model relies on a user-defined parameter, referred to as bulking factor, to control the volume of rubble relative to the *in-situ* rock volume (Bechtel SAIC Company, LLC, 2004b, pp. 6-217 through 6-220; Gute, et al., 2003, pp. 4-2 through 4-5). The UDEC-Voronoi model, on the other hand, does not need a user-specified bulking factor, but could be used to calculate bulking factor if the model indicates rubble formation as an outcome.

Although the UDEC-Voronoi model may be a useful tool for gaining insight into aspects of potential drift degradation in lithophysal rock, making a case that the model should be relied on for quantifying drift-degradation attributes, however, needs a careful examination of the model assumptions. The UDEC-Voronoi model includes several assumptions that could unrealistically constrain the calculated degraded drift configuration, amount of rubble, and load transmission through rubble. First, the UDEC-Voronoi model used for DOE calculations was constrained by an elastic boundary at 1.86 drift diameters above the drift roof (Bechtel SAIC Company, LLC, 2004b, Figure 6-116, p. 6-156), which implies the drift represented by the model is physically constrained to not degrade vertically more than 1.86 drift diameters. DOE did not justify the assumption. Second, as discussed in Section 4.3.1 of this report, several properties of the UDEC-Voronoi model that may influence calculated results were not calibrated against any data. These include tensile strength and stress-strain behavior under confined compression and the postpeak phase of unconfined compression. Although DOE indicated that the tensile and stress-strain behavior calculated from the model look realistic, calibrating these properties against data would increase confidence in using the model to derive quantitative results that could affect performance estimates. Third, the rock mass is represented in the UDEC-Voronoi model using bonded equidimensional polygons such that only equidimensional blocks with an average side length of 0.2 or 0.3 m [0.7 or 1.0 ft] could result from any fracturing of the rock.

DOE indicated such block representation is appropriate for the lithophysal rock units at Yucca Mountain (Bechtel SAIC Company, LLC, 2004b, pp. 6-150 and 6-225).

An examination of DOE information, however, suggests the lower lithophysal rock unit is characterized by nonrandom fracture orientation (i.e., distinct fracture sets) with heterogeneous spacing (i.e., direction-dependent spacing) and nonuniform distribution of lithophysae. In contrast to DOE results, a number of studies suggest a combination of fracture and lithophysal characteristics is expected to produce a wide range of rock-block sizes and shapes.

- A CNWRA analysis (Smart, et al., 2006) of subsurface fracture data from the Exploratory Studies Facility and Enhanced Characterization of the Repository Block Cross Drift indicates clearly definable fracture sets occurring in both lithophysal and nonlithophysal units of the Topopah Spring Tuff. The analysis indicates these sets occurring in the population of both large {i.e., trace lengths >1 m [3.3 ft]} and small {i.e., trace lengths <1 m [3.3 ft]} fractures. The occurrence of well-defined fracture sets contrasts with a DOE statement that fracture sets in the lower lithophysal unit are not as clearly defined as in the middle nonlithophysal unit (Bechtel SAIC Company, LLC, 2004b, p. 6-150).

- Although DOE states that average fracture spacing in the lower lithophysal zone is less than 1 m [3.3 ft] and at selected locations much smaller {i.e., on the order of 10–30 cm [3.9–11.8 in]}, DOE does not distinguish between the spacing of large fractures versus those for small fractures. Smart, et al. (2006) estimate the spacing for the large fracture sets is on the order of several meters {mean spacing 3–9 m [9.8–29.5 ft]; median spacing 1–6 m [3.3–19.7 ft]}, whereas the spacing for smaller fractures is on the order of tens of centimeters to meters {mean spacing 10 cm [3.9 in] to 1 m [3.3 ft]; median spacing 3–12 cm [1.2–4.7 in]}. Further, the DOE statement implies that fracture spacing is constant in all directions, whereas the data indicate spacing varying greatly from one fracture set to another based on the analysis by Smart, et al. (2006).

- Although DOE states the lithophysae are uniformly distributed in the lithophysal units (Bechtel SAIC Company, LLC, 2004b, p. 6-150), their data could lead to a different conclusion. Lithophysal abundance in the cross drift, for example, can vary by as much as 50 percent over a spatial extent of tens of meters (Bechtel SAIC Company, LLC, 2004b, Figure O-2, p. O-3). Likewise, the nonuniform distribution of lithophysae is evident at the meter scale (and smaller) on individual panel maps (e.g., Bechtel SAIC Company, LLC, 2004b, Figures O-3 through O-8, pp. O-5 through O-10).

The combination of nonrandom fracture orientation (i.e., distinct fracture sets) with heterogeneous spacing (i.e., direction-dependent spacing) and nonuniform distribution of lithophysae implies degradation of drifts in the lower lithophysal rock unit could produce a wide range of rock-block sizes and shapes. The representation of the rock mass using uniform-sized and equidimensional blocks in the UDEC-Voronoi model, therefore, could result in rubble characteristics and degraded-drift configurations that are inconsistent with the potential reality. The DOE approach of using calculated results from the UDEC-Voronoi model to directly quantify the potential mechanical loading of a drip shield owing to rubble accumulations and the degraded-drift geometry, therefore, could misrepresent the potential effects of drift degradation.

The analytical abstraction of rubble accumulation based on constraining the degraded-drift volume to satisfy a mass-balance between the rubble and the *in-situ* rock (Bechtel SAIC

Company, LLC, 2004b, pp. 6-217 through 6-220; Gute, et al., 2003, pp. 4-2 through 4-5) provides a robust approach to quantifying the amount of rubble accumulations and loading. The analytical model is independent of any definition of mechanical relationships within the rock mass or rubble. The analytical approach includes assumptions regarding the shape of a degraded drift, value of bulking factor, and full-load transmission through rubble. These assumptions reasonably can be justified, as discussed herein.

Shape of Degraded Drift

The potential shape of a degraded drift can be inferred from thermal-mechanical analysis reported by Ofoegbu, et al. (2006), which indicates unsupported emplacement drifts subjected to thermal loading could degrade through progressive spallation caused by thermally induced overstress. Spallation is estimated to initiate in a zone approximately 0.75 drift diameter wide around the drift perimeter and a few tens of centimeters deep. For the lowest grade lithophysal rock, which is characterized by a rock-mass Young's modulus of approximately 5 GPa [725 ksi] based on DOE information (Section 3.2 of this report), spallation is estimated to initiate on the sidewalls of the drift and progress laterally first and vertically thereafter. For the highest grade lithophysal rock, which is characterized by a rock-mass Young's modulus of approximately 20 GPa [2,900 ksi] based on DOE information (Section 3.2 of this report), spallation is estimated to initiate at the drift roof and progress vertically.

A chimney-shaped configuration is estimated to result from vertical progression of roof spallation. A laterally enlarged configuration is estimated to result from lateral progression of sidewall spallation followed by vertical progression at a later stage. Such a configuration can be represented using a trapezoidal shape. The results of the thermal-mechanical analysis (Ofoegbu, et al., 2006), therefore, can be interpreted to infer the configuration of a degraded drift may vary between a chimney shape and a trapezoidal shape. The proportion of potential chimney- and trapezoidal-shaped degraded drifts in lithophysal rock can be estimated based on the proportion of the various lithophysal-rock categories.

DOE information (Bechtel SAIC Company, LLC, 2004b, pp. 6-151 through 6-152) indicates approximately 10 percent of lithophysal rock belongs to the lowest grade category, and approximately 30 percent belongs to the highest grade category. The middle categories, approximately 60 percent, consist of rocks with a Young's modulus of approximately 8–17 GPa [1,160–2,466 ksi]. A large proportion of the middle-category rocks would have similar behavior as the high-grade lithophysal rock, whereas a small fraction would behave like the low-grade category. Therefore, a large fraction of degraded drifts in lithophysal rock would be expected to be chimney shaped and a small fraction expected to be trapezoidal shaped based on the CNWRA analyses. A preponderance of chimney shapes also would be consistent with sources cited in Gute, et al. (2003, p. 4-9), which suggest the chimney shape would be prevalent in homogeneous and relatively weak rock. Therefore, based on the information discussed in this and the foregoing paragraphs, a preponderance of chimney-shaped degraded configurations would be expected and could be represented using 25-percent trapezoidal shape and 75-percent chimney shape. DOE information (Bechtel SAIC Company, LLC, 2004b, p. 6-174) indicates seismically induced drift degradation may result predominantly in the trapezoidal shape.

Bulking Factor

The bulking factor for a rock relates the *in-situ* volume V of a rock block to the volume of rubble V_B formed after the block falls into the drift opening. DOE described the relationship using a bulking factor B defined as $V_B/V - 1$, which implies values of bulking factor generally smaller than 1.0 (Bechtel SAIC Company, LLC, 2004b, pp. 6-217 through 6-220). Gute, et al. (2003, p. 4-2) defined bulking factor slightly differently as the ratio V_B/V. A value of bulking factor based on the Gute, et al. (2003) definition (e.g., 1.25) would be 1.0 greater than the equivalent value of bulking factor based on the DOE definition (i.e., 0.25).

UDEC-Voronoi modeling of lithophysal rock (Bechtel SAIC Company, LLC, 2004b, Figure 6-179, p. 6-233) gave bulking factors in the range of 0.1–0.4 (i.e., 1.1–1.4), with the majority of the values in the range of 0.15–0.25 (i.e., 1.15–1.25). The bulking factor distribution described in Ibarra, et al. (2006, p. 5-3) is based on the DOE information.

Load Transmission Through Rubble

DOE stated that the vertical load transferred to a drip shield from rubble should be smaller than the weight of rubble above the drip shield, because a part of the rubble weight would be transferred to the adjacent drift wall through friction (Bechtel SAIC Company, LLC, 2004b, p. 6-232). Results from UDEC-Voronoi modeling of a seismically induced drift collapse indicate a fraction of the rubble load being shed to the sides and away from the drip shield (Bechtel SAIC Company, LLC, 2004b, Figure 6-117, p. 6-231). Such load shedding, referred to as arching, could occur in rubble formed from a rapid collapse, such as would be caused by a seismic event when a large mass of rubble could fall almost instantaneously. As discussed in Section 4.3.2.1, however, independent analysis (Ofoegbu, et al., 2006) suggests potential thermally induced rubble forming in small increments. The amount of rubble formed in each increment is estimated to be small because it would result from a thin zone of over stressed rock. Small increments of rubble accumulation likely would be supported on the immediately underlying surface, thereby reducing the likelihood of load shedding or arching. Therefore, it can be inferred based on the CNWRA analysis that the full weight of thermally generated rubble estimated to potentially overlie the drip shield should be considered in evaluating the drip shield performance.

4.3.4.2 Rate of Rubble Accumulation

DOE information does not include the rate of rubble accumulation, except for seismically generated rubble, for which the accumulation rate could be estimated based on the recurrence rate of seismic events.

An accumulation rate for thermally generated rubble could be estimated based on results from thermal-mechanical analysis (e.g., Ofoegbu et al., 2006) and rock failure rates inferred from a typical stress-strain curve for brittle rocks (e.g., Figure 4-3). Typically, an element of brittle rock subjected to a stress equal to its peak strength (Point P in Figure 4-3) fails instantaneously (i.e., at the time the applied stress equals the peak strength). If the applied stress is less than the peak strength but is sustained (e.g., line segments AA_f, BB_f, or CC_f in Figure 4-3), delayed failure occurs at a time that increases exponentially as the applied stress decreases. Failure does not occur if the applied stress is smaller than approximately 60 percent of the peak strength (e.g., Point C in Figure 4-3) [Goodman (1980, p.74), Lajtai and Schmidtke (1986)]. Ofoegbu, et al. (2006), using rock mass properties and a thermal loading based on DOE information, calculated that thin zones of rock near the drift perimeter would be subjected to stresses equal to the peak strength during approximately 1,000 years after waste emplacement. Ofoegbu, et al. (2006) interpreted the calculated overstress to imply potential thermally induced progressive spallation of the drift roof and sidewall, which could result in the drifts degrading to fill with rubble. Such spallation would occur during the time the applied stress would be equal to the peak strength, which Ofoegbu, et al. (2006) calculated would occur during approximately 1,000 years after waste emplacement. A rubble accumulation rate could be estimated based on such information by assuming a drift will degrade at a constant rate until it fills with rubble.

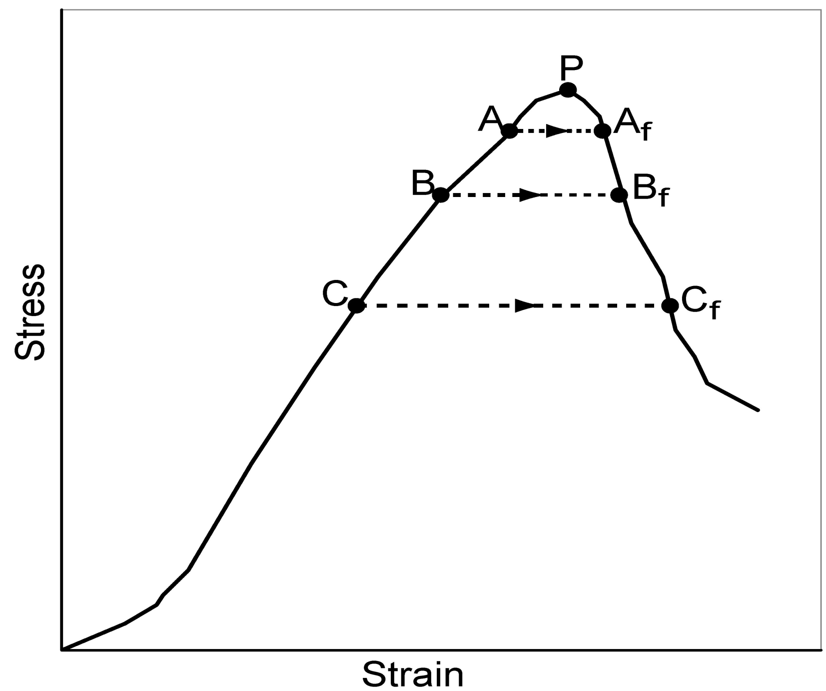

Figure 4-3. Typical Stress-Strain Curve for Brittle Rock. Failure Occurs Instantaneously if Stress Equals the Peak Strength, P. Delayed Failure Occurs if Stress is Greater Than or Equal to C Value but Less Than P Value. Points A_F, B_f, and C_f Represent Failure States for a Constant Stress of A, B, or C, Respectively. A Stress Less Than C Value Will Not Cause Failure. Time to Failure Increases Exponentially as Stress Decreases From A to C Values (Lajtai and Schmidtke, 1986; Goodman, 1980, p. 74).

5 POTENTIAL EFFECTS OF DRIFT DEGRADATION ON ENGINEERED BARRIER SYSTEM PERFORMANCE

This chapter discusses the assessment of potential effects of drift degradation on the mechanical integrity of engineered barrier components and thermohydrologic parameters important to seepage and corrosion. The technical bases for DOE disposition of related features, events, and processes also are discussed.

5.1 Mechanical Behavior of Drip Shield and Waste Package

DOE screening of features, events, and processes pertaining to drip shield and waste package mechanical degradation relies on the assertion that DOE drip shield design is structurally competent to protect waste packages from the drift degradation effects (Bechtel SAIC Company, LLC, 2004c). Consequently, waste packages will be subjected to mechanical stresses only if strong seismic events take place and dynamic interaction between the different engineered barriers occurs. CNWRA staff evaluation (Ibarra, et al., 2005), however, indicates a high likelihood of drip shield collapse under credible loading scenarios that may result in mechanical interaction of the drip shield and the waste package. Therefore, the structural performance of drip shields and waste packages under nominal and seismic loading scenarios are examined to identify loading conditions that may lead to engineered barrier damage. Tables 5-1 and 5-2 summarize the loading scenarios and the screening decisions used in the performance assessment codes developed by DOE and independently by the staff.

5.1.1 Summary of DOE Evaluation of Engineered Barriers Under Nominal Loading Scenarios

The nominal scenario assumes that the repository performs under the conditions expected to occur in the future. Nominal scenario conditions include thermal loading, stress effects of the excavated openings, any time-dependent weakening of rock, and seismic ground motion with a mean annual probability of exceedance of 5×10^{-4} or greater (Bechtel SAIC Company, LLC, 2004c, p. 6-47).

As shown in Sections 4.1 and 4.2, DOE studies indicate that the emplacement drifts will remain stable for 10,000 years under nominal scenario conditions. For the lithophysal rock, which accounts for 85 percent of the repository rock, DOE analyses predict small accumulations of rubble caused by thermal loading or high probability ground motion events (Bechtel SAIC Company, LLC, 2004c,e). For the nonlithophysal rock, DOE predicts isolated rockfall blocks and estimates that the largest rockfall block for the nominal scenario corresponds to a block of 2.72 metric tons [6.0 kips] originated by vibratory ground motions (Bechtel SAIC Company, LLC, 2004e,f). Thus, the only loading condition related to drift degradation that DOE evaluates refers to isolated rock blocks impacting the engineered barriers (Case 1 of Table 5-1), as indicated in the Features, Events, and Processes 2.1.03.07.0B (Bechtel SAIC Company, LLC, 2004e). According to DOE, damage to the drip shield from rockfall impact can be excluded based on a low consequence screening criterion because this barrier can withstand even the rockfall block impacts caused by postclosure seismic events (Subsection 5.1.2). In addition, waste package damage due to rockfall (Case 2 of Table 5-1) is excluded based on a low probability screening criterion, because the drip shield would provide adequate protection to the waste packages (Bechtel SAIC Company, LLC, 2004e). DOE also indicates that mechanical loading at the interfaces between the waste package and pallet was analyzed (Case 4 of Table 5-1), and the contact stresses are less than the stress threshold for initiation of stress corrosion cracking (Bechtel SAIC Company, LLC, 2004e). In fact, DOE excludes all physical effects of static loading that may occur at the interfaces between different barriers based on a low consequence screening criterion (Bechtel SAIC Company, LLC, 2004e).

Creep processes, which may lead to deformation of the engineered barriers in response to deviatoric stress or internal void space, are excluded by DOE based on a low probability screening criterion (Cases 5 and 6 of Table 5-1). The waste package outer shell is made of Alloy 22 and, according to DOE, it will be exposed to temperatures below 300 °C [572 °F]. DOE states, however, that creep deformation or creep fracture for nickel-based alloys is not expected at temperatures below 650 °C [1,202 °F] (Bechtel SAIC Company, LLC, 2004e). The temperature in the drip shield, which is made of titanium alloys, will be also less than 300 °C [572 °F]. DOE indicates that between 200 °C and 315 °C [392 °F and 599 °F], the deformation of many titanium alloys loaded to yield point does not increase with time (Bechtel SAIC Company, LLC, 2004e). Given that creep rates decrease at lower temperatures, DOE concludes that creep deformation of the engineered barriers will not occur to any appreciable extent under repository exposure conditions.

DOE also excludes thermal sensitization of the material based on a low probability screening criterion (Cases 7 and 8 of Table 5-1). Therefore, DOE does not consider phase changes in the engineered barrier materials that may occur during long-term storage at moderately hot temperatures, resulting in stress corrosion cracking, intergranular corrosion, or mechanical degradation.

In summary, DOE excludes from the Total-system Performance Assessment code all the nominal loading scenarios that could affect the engineered barriers, such as static loads and dynamic loads due to rockfall, as well as the potential effects of creep processes and temperature variation.

5.1.2 Summary of DOE Evaluation of Engineered Barriers Subjected to Seismic Events

According to DOE, partial or total drift collapse only occurs within seconds of the arrival of ground motions with a mean annual frequency of exceedance of 1×10^{-5} or smaller (Bechtel SAIC Company, LLC, 2004b,g). Based on this characterization of drift damage, DOE evaluates the performance of the engineered barriers under three seismic loading conditions. The first loading condition assumes the emplacement drifts remain intact while the engineered barrier components move in response to seismic ground motions. The second condition assumes the drifts remain largely intact but individual rock blocks could detach from the drift roof or sidewall and strike the drip shield. The third condition assumes emplacement drifts collapse onto the drip shield when subjected to strong seismic events.

DOE assessment of engineered barriers performance under the first loading condition is summarized through Features, Events, and Processes 1.2.03.02.0A, which evaluates the disruption of the drip shields and waste packages through vibration damage or contact between engineered barriers (Bechtel SAIC Company, LLC, 2004c). The evaluation includes damage from impacts between the waste package and emplacement pallet and from impacts between adjacent waste packages. Damage from impacts between the waste package and the drip shield is negligible because the drip shield is unrestrained and can move freely because the drifts are assumed intact (Bechtel SAIC Company, LLC, 2004g). DOE also indicates that the mechanical response of the drip shield to vibratory ground motions has the potential to damage the drip shield as a barrier to flow. The performance assessment code, however, does not include this failure mode, because DOE studies predict that stress corrosion cracks on the drip shield would be plugged with corrosion products, and advective flux of liquid through this barrier would be very limited (Case 1 of Table 5-2). Separation of adjacent drip shield sections is also excluded because (i) the interconnected drip shields move synchronously in open drifts (i.e., drifts unfilled with rockfall rubble) and (ii) frictional forces from small amounts of rubble can restrain the relative motion between adjacent drip shields (Bechtel SAIC Company, LLC, 2004g). Additionally, the DOE performance assessment code only includes potential damage to the waste package and the cladding (Case 2 of Table 5-2). The criteria for failure are based on a residual stress threshold of between 80 and 90 percent of the yield strength for Alloy 22 for the waste package outer barrier and a residual stress threshold of 50 percent of the yield strength for Titanium Grade 7 for the drip shield plates (Bechtel SAIC Company, LLC, 2004g,h). Note that DOE is currently performing vibratory analyses that consider potential drift collapse. For instance, Sevougian (2006) indicates that kinematic analyses are being performed to produce histories of multiple waste package impacts, using a model that considers an intact drip shield in a collapsed-drift environment. These calculations, however, are works in progress and have not been implemented in the performance assessment code.

DOE assessment of the behavior of engineered barriers under the second loading condition is summarized through Features, Events, and Processes 1.2.03.02.0B, which evaluates the effects of seismic activity leading to rockfall that could impact engineered barriers (Bechtel SAIC Company, LLC, 2004c). DOE indicates that the maximum deflection in the drip shield components due to rockfall block impact is 254 mm [10.0 in] and is less than the minimum gap between the drip shield and the waste package of 367 mm [14.5 in] (Bechtel SAIC Company, LLC, 2004c). This impact would be triggered by a seismic event with mean annual frequency of exceedance of 1×10^{-7} and involves an 11.5-metric ton [12.7-ton] block with the largest kinetic energy reported in DOE analyses (Bechtel SAIC Company, LLC, 2004c,f). DOE notes (Bechtel SAIC Company, LLC, 2004e,g) that the impact of large rock blocks may lead to drip shield-damaged areas susceptible to stress corrosion cracking, but the amount of potential water flow through the resulting crack network would be insignificant (Case 3 of Table 5-2). If the drip shield would remain intact, damage to the waste package or cladding from rock blocks does not need to be evaluated (Case 4 of Table 5-2).

DOE assessment of the engineered barriers behavior under the third loading condition is summarized through Features, Events, and Processes 1.2.03.02.0C, which evaluates the effects of seismic activity leading to drift collapse that could affect the engineered barriers (Bechtel SAIC Company, LLC, 2004c). DOE studies show that vibratory ground motions can cause the host rock to fail in the lithophysal zones (Bechtel SAIC Company, LLC, 2004b). Therefore, DOE evaluated the drip shield structural performance under static loading and documented the calculations in the report Structural Stability of a Drip Shield under Quasi-Static Pressure (not publicly available). A summary of this report (Bechtel SAIC Company, LLC, 2004g,i) indicates that DOE developed six random loading configurations that exhibit vertical load pressures from 109 to 155 kPa (15.8 to 22.5 psi) and average lateral-to-vertical load ratios ranging from 0.12 to

0.78 (i.e., the average of the horizontal loads of both drip shield walls ranges within 12 and 78 percent of the vertical load). DOE indicates that the drip shield is structurally stable for the six evaluated loading realizations.

DOE computed the mean vertical pressure from the six individual realizations as 128 kPa [18.5 psi], whereas the mean of the average lateral-to-vertical load ratio is 0.41. To estimate a safety factor, DOE increased the density of rubble at the six realizations by 2.5, 3, and 4 times, and computed the mean loading configuration at each level. Because the factor is applied to the density of the rubble, the increase in loading is not linearly proportional. For instance, for a density multiplier of 2.5, the vertical pressure is 264 kPa [37.8 psi], and the mean lateral-to-vertical load ratio is reduced to 0.29 (Bechtel SAIC Company, LLC, 2004i). DOE structural analyses predict that the drip shield would undergo severe plastic deformation in its support beams at a density multiplication factor of four. DOE concludes that there is a safety factor of approximately three for the drip shield under static loading (Case 5 of Table 5-2).

Based on the results of DOE analyses and screening arguments for the relevant features, events, and processes as discussed in this subsection, the only potential damage to engineered barriers included in the DOE Total System Performance Assessment Code is damage to waste packages subjected to vibratory ground motions in an open drift environment (i.e., based on the first loading condition).

5.1.3 CNWRA Staff Evaluation of DOE Assessment of Engineered Barriers Under Nominal Loading Scenarios

The DOE assessment of engineered barriers for the nominal scenario does not consider a complete range of credible loading conditions or parameter ranges and processes that could affect the engineered barriers performance.

Although DOE only considers drift degradation due to strong seismic events, CNWRA staff analyses indicate thermal loading could cause the drifts to collapse within a few hundreds of years (Section 4.1 and 4.2), and the magnitude of the vertical loads would be larger than those proposed by DOE due to vibratory ground motions (Section 5.1.2). Gute, et al. (2003) evaluated the drip shield structural performance and concluded that whereas potential mitigating factors reduce the importance of discrete rock block impacts on the drip shield (Cases 1 and 2 of Table 5-1), static loading from accumulated rubble could cause the drip shield to buckle (Case 3 of Table 5-1).

A similar evaluation of a modified DOE drip shield design (Bechtel SAIC Company, LLC, 2004f), which is focused on the drip shield performance under static loads (Case 3 of Table 5-1), indicates the current drip shield design may not withstand the expected static loading conditions and that structural instability would be triggered by plastic buckling of the drip shield columns (Ibarra, et al., 2005). For a baseline model with an expected vertical pressure of 300 kPa [43.5 psi] and an average lateral-to-vertical load ratio of 0.35, Ibarra, et al. (2005) estimated that the maximum vertical load that the drip shield can withstand (vertical load carrying capacity) is slightly less than 300 kPa [43.5 psi]. Thus, the safety factor for the baseline case is less than one. For most static loading configurations, the evaluation concludes that the drip shield failure mechanism is plastic buckling of the drip shield columns, which is the failure mode reported by Gute, et al. (2003) and DOE (Bechtel SAIC Company, LLC, 2004g,i).

DOE also investigated the drip shield performance under static loading, although in the DOE assessment, the accumulated rubble is caused by strong seismic events. As presented in Section 5.1.2, DOE estimated a safety factor of about three for an initial vertical load of 128 kPa [18.5 psi]. The DOE static loading configuration is similar to the CNWRA baseline case in the lateral-to-vertical load ratio, but DOE-expected vertical loads are lower than CNWRA-expected vertical demand of 300 kPa [43.5 psi]. Thus, under the same demands and input parameters, the difference in the structural response provided by DOE and CNWRA numerical models would be relatively small, considering that different structural programs and structural modeling are used and that structural instability assessment requires estimating material nonlinear behavior and geometric nonlinearities. Because of the discrepancy in the loading magnitude, however, the safety factor obtained by the CNWRA staff for the baseline case is almost three times lower than that of DOE.

Second, the DOE assessment does not include a complete range of parameter values that may further reduce the drip shield vertical load carrying capacity. A parametric study performed by Ibarra, et al. (2005) indicates that the average lateral-to-vertical load ratio is the parameter of the nominal scenario with the largest influence on the drip shield vertical load carrying capacity. In this regard, DOE indicates that “the distribution of the point loads in the cross-section and along the drip shield and their magnitude vary significantly” (Bechtel SAIC Company, LLC, 2004i). Nevertheless, it appears that DOE calculations to obtain the safety factor did not consider lateral-to-vertical load variation, because DOE increased “the vertical and lateral pressures in tandem, without additional assumptions about extreme vertical or lateral loads” (Bechtel SAIC Company, LLC, 2004g). To evaluate the ultimate drip shield capacity, DOE performed three additional simulations using an average load distribution of the six individual loading realizations (Bechtel SAIC Company, LLC, 2004i). In addition, DOE did not provide technical basis to support the assumption that a central measure of dispersion obtained from only six realizations would be representative of the potential load distribution variation.

Also, DOE indicates that for a density multiplier of one, the drip shield is structurally stable for the six loading realizations. Some of these loading realizations, however, exhibit high lateral loads that may lead to high stresses and strains in the weakest areas of the support frames. Also, the drip shield base may move inward if the resultant forces overcome the frictional force at the base. The DOE model includes lateral constraints limiting the base displacement that represent the physical constraints provided by the pallet, which is composed of two base supports attached by tubular elements. However, the pallet can constrain the drip shield only if the contact occurs at the pallet base, because the tubular elements are flexible components. Moreover, two pallet base supports are approximately one-fifth of the drip shield length. Thus, it is likely that the drip shield support beam (column) will not interact with the base support pallet. Also, the pallet cannot necessarily be assumed as a fixed boundary condition, even in the cases where the drip shield column makes contact with the pallet support. Therefore, it is possible that some of DOE drip shield analyses that include high lateral loads are structurally stable because the model overestimates the lateral constraint provided by the pallet, precisely in the region of the drip shield column where DOE and independent analyses predict failure initiation.

Third, the DOE assessment does not include a complete range of processes that could reduce the drip shield vertical load carrying capacity. A CNWRA staff evaluation of the effect of creep on the drip shield performance (Ankem, 2006) suggests that creep deformation caused by a permanent static load may decrease the drip shield strength capacity if the stress levels approach or exceed the material yield strength (Case 5 of Table 5-1). Conversely, DOE indicates that the deformation of many titanium alloys loaded to yield point does not increase with time at the expected temperature in the repository (Bechtel SAIC Company, LLC, 2004e). Although the available data for creep of titanium materials at the yield stress or below is not conclusive, creep failure is likely to occur once the yield stress of the titanium material is exceeded under permanent static loading. Analyses performed by Ibarra, et al. (2006) indicate this phenomenon would significantly affect the drip shield performance because the titanium material may exceed the yield stress at about half of the demand required to cause structural instability.

Analyses performed by Ibarra, et al. (2005) also indicate that the in-drift temperature may modify the drip shield strength capacity by almost 50 percent if temperature increases from the base temperature of 150 °C [302 °F] to an estimated upper bound of 316 °C [601 °F] (Case 7 of Table 5-1). Analyses performed by Manepally, et al. (2004) indicate that the engineered barriers may exceed the base temperature if drifts degrade within the first hundreds of years. On the other hand, DOE evaluates drip shield performance at 150 °C [302 °F] because they estimate that drift degradation only occurs as a result of strong seismic events that would occur after several thousands of years, when the in-drift temperature is significantly below 150 °C [302 °F]. Thus, if thermal-induced drift degradation is a credible scenario, DOE assessment does not include the effects of the complete range of temperature.

Also, the DOE assessment does not include the effects of differential settlement of the drip shield owing to degradation of the grid of carbon steel beams included in the invert. Ibarra, et al. (2005) note that differential settlement could cause the drip shield capacity to decrease due to additional geometric nonlinearities (Case 9 of Table 5-1).

Therefore, CNWRA staff analyses show that the drip shield performance under nominal loading scenarios must be significantly better than that provided by the current design to prevent structural instability. Ideally, the system performance should remain within the elastic range under any potential nominal loading configuration because inelastic performance triggers additional failure modes, such as localized corrosion and creep. Moreover, it is unlikely that a structural system performing in the inelastic range under static loads will have sufficient inelastic absorption energy capacity to withstand the expected postclosure seismic events.

Regarding the waste package performance, mechanical interaction between the waste package and a collapsed drip shield may lead to damage of the waste package outer shell. The waste package consists of an external cylinder (outer shell) made of Alloy 22 material and an internal cylinder made of stainless steel (inner vessel). Ibarra, et al. (2006) evaluated drip shield–waste package mechanical interaction, assuming the inner vessel function is limited to providing structural support and that the outer shell fails if the strain corresponding to the ultimate tensile strength of the material is reached. The study indicates that the mechanical interaction could lead to high localized plastic stresses in the waste package, but a large safety margin against breaching of the waste package outer barrier under static loading was obtained (Case 4 of Table 5-1). Nevertheless, staff are concerned that DOE does not evaluate the effect of waste package mechanical interaction with other engineered barriers for the nominal scenario.

5.1.4 CNWRA Staff Evaluation of DOE Assessment of Engineered Barriers Under Seismic Loading Scenarios

The DOE assessment of engineered barriers for the seismic scenario does not include a complete range of credible loading conditions that could affect the performance of the drip shield or waste package during and after a seismic event.

First, although DOE considers that seismic events may lead to drift collapse, DOE dynamic analyses do not include the presence of rock rubble during the seismic event (Case 7 of Table 5-2). Rather, DOE states that only a strong seismic event can trigger drift collapse, and "coupled effects from multiple seismic events are not considered because seismic hazards with the potential to have a significant impact on engineered barriers are anticipated to occur very rarely, if at all, …" for 10,000 years (Bechtel SAIC Company, LLC, 2004g). Thus, DOE does not evaluate possible effects of subsequent seismic events on a collapsed drift environment. However, because DOE indicates that drift collapse will take place within the first seconds of the seismic event, the drip shield dynamic analyses should consider static loading, even if the drift is initially intact and multiple seismic events are disregarded. In this regard, CNWRA staff estimate that drift degradation is likely to precede strong seismic events because of thermal-induced drift degradation and multiple seismic events. Therefore, drip shield dynamic analyses should include initial static loading.

The CNWRA staff also note that DOE analyses show that seismic events may significantly increase the static loading. Appendix P of the Drift Degradation Analysis report (Bechtel SAIC Company, LLC, 2004b) presents the dynamic loads on the top and sides of a drip shield initially surrounded by rubble that undergoes a seismic event with a mean annual frequency of exceedance of 1×10^{-6}. The transient dynamic loads cause drip shield pressures {1,500–2,000 kPa [217–290 psi]} that are more than one order of magnitude larger than the initial static loading {about 100 kPa [14.5 psi]}. Moreover, to obtain the average pressures, DOE analyses subdivide the drip shield cross section into 30 segments. The pressure on some of these segments can be much higher than the average pressure. For this example, some segments reach pressures of 5,000 kPa [726 psi], which is about 50 times the average initial static loading. In these analyses, the drip shield does not exhibit structural instability, because it was modeled to prevent inelastic structural behavior. Ibarra, et al. (2005), however, indicate that the current drip shield design is unable to withstand seismic events associated with mean annual frequencies of exceedance lower than 1×10^{-5} when initial static loading is included (Case 7 of Table 5-2).

DOE also indicates that separation of adjacent drip shield sections is unlikely. Note that one of the main DOE reasons for excluding this failure mechanism is the presence of rubble that restrains the drip shield motion. According to DOE, "smaller events (with a rate of 10^{-5} per year) can contribute to the buildup of rockfall around the drip shield before an extreme event occurs" (Bechtel SAIC Company, LLC, 2004i). Because the CNWRA staff also estimate that strong seismic events will very likely occur after drift degradation, this failure mechanism is not independently evaluated. Observe, however, that DOE's argument for excluding drip shield separation could also be used to establish the need for dynamic analyses of the drip shield when surrounded by rubble.

Table 5-1. DOE and NRC/CNWRA Studies on the Effect of Drift Degradation on Engineered Barriers for Nominal Loading Scenarios			
	Nominal Loading Scenario	**DOE Features, Events, and Processes Screening Decision**	**Proposed Screening by the Staff**
1	Isolated Blocks Impacting the Drip Shield	2.1.03.07.0B* Excluded Low Consequence	Excluded†
2	Isolated Blocks Impacting the Waste Package	2.1.03.07.0A*§ Excluded Low Consequence	Excluded†
3	Drip Shield Structural Performance Under Static Loading	Not Evaluated	Included‡
4	Interface Between Drip Shield and Waste Package	2.1.06.07.0B* Excluded Low Consequence	Included§
5	Effect of Creep on Drip Shield Materials	2.1.07.05.0B * Excluded Low Probability	Included§‖
6	Effect of Creep on Waste Package Materials	2.1.07.05.0A* Excluded Low Probability	Not Evaluated
7	Effect of Temperature on Drip Shield Performance	2.1.11.06.0B* Excluded Low Probability	Included‡
8	Effect of Temperature on Waste Package Performance	2.1.11.06.0A* Excluded Low Probability	Excluded§
9	Effect of Invert Degradation on Drip Shield Performance	Not Evaluated	Not Evaluated‡
10	Effect of Uniform Corrosion on Drip Shield Performance	2.1.03.01.0A* Included	Included‡
11	Effect of Uniform Corrosion on Waste Package Performance	2.1.03.01.0B* Included	Included§

* Bechtel SAIC Company, LLC. "FEPs Screening of Processes and Issues in Drip Shield and Waste Package Degradation." ANL–EBS–PA–000002. Rev. 03. Las Vegas, Nevada: Bechtel SAIC Company. 2004.
† Gute, G.D., G. Ofoegbu, F. Thomassy, S. Hsiung, G. Adams, A. Ghosh, B. Dasgupta, A.H. Chowdhury, and S. Mohanty. "MECHFAIL: A Total-System Performance Assessment Code Module for Evaluating Engineered Barrier Performance Under Mechanical Loading Conditions." CNWRA 2003–06. San Antonio, Texas: CNWRA. 2003.
‡ Ibarra, L., T. Wilt, G. Ofoegbu, and A. Chowdhury. "Structural Performance of Drip Shield Subjected to Static and Dynamic Loading." San Antonio, Texas: CNWRA. 2005.
§ Ibarra, L., T. Wilt, G. Ofoegbu, R. Kazban, F. Ferrante, and A. Chowdhury. "Drip Shield-Waste Package Mechanical Interaction." San Antonio, Texas: CNWRA. 2006.
‖ Ankem, S. "A Literature Review of Low Temperature (<0.25Tm) Creep Behavior of a, a-b and b Titanium Alloys." San Antonio, Texas: CNWRA. 2006.

Table 5-2. DOE and NRC/CNWRA Studies on the Effect of Drift Degradation on Engineered Barriers for Disruptive (Seismic) Loading Scenarios

	Seismic Loading Scenario	DOE Features, Events, and Process Screening Decision	Proposed Screening by the Staff
1	Damage to the Drip Shield Due to Vibration and Contact with Other Barriers	1.2.03.02.0A* Excluded Low Consequence	Not Evaluated
2	Damage to the Waste Package and Cladding Due to Vibration and Contact with Other Barriers	1.2.03.02.0A* Included	Not Evaluated
3	Isolated Blocks Impacting the Drip Shield Due to Seismic Events	1.2.03.02.0B* Excluded Low Consequence	Excluded[‡]
4	Isolated Blocks Impacting the Waste Package Due to Seismic Events	1.2.03.02.0B* Excluded Low Probability	Excluded[†‡]
5	Drip Shield Under Static Loading Caused by Seismic Events	2.1.07.05.0C* Excluded Low Consequence	Included[†‡]
6	Waste Package Under Static Loading Caused by Seismic Events	2.1.07.05.0C* Excluded Low Probability	Included[§]
7	Drip Shield Under Dynamic Loading Including Accumulated Rubble	Not Evaluated	Included[†‡]
8	Waste Package Under Dynamic Loading Including Accumulated Rubble	Not Evaluated	Included[§]
9	Effect of Uniform Corrosion on Drip Shield Seismic Evaluation	1.2.03.02.0A*[‖] Included	Included[§]
10	Effect of Uniform Corrosion on Waste Package Seismic Evaluation	1.2.03.02.0A*[‖] Included	Included[§]
11	Effect of Seismic Faulting Events on Engineered Barriers	1.2.02.03.0A*[‖] Included	Not Evaluated[§]

* Bechtel SAIC Company, LLC. "FEPs Screening of Processes and Issues in Drip Shield and Waste Package Degradation." ANL-EBS-PA-000002. Rev. 03. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2004.
† Ibarra, L., T. Wilt, G. Ofoegbu, and A. Chowdhury. "Structural Performance of Drip Shield Subjected to Static and Dynamic Loading." San Antonio, Texas: CNWRA. 2005.
‡ Gute, G.D., G. Ofoegbu, F. Thomassy, S. Hsiung, G. Adams, A. Ghosh, B. Dasgupta, A.H. Chowdhury, and S. Mohanty. "MECHFAIL: A Total-System Performance Assessment Code Module for Evaluating Engineered Barrier Performance Under Mechanical Loading Conditions." CNWRA 2003–06. San Antonio, Texas: CNWRA. 2003.
§ Ibarra, L., T. Wilt, G. Ofoegbu, R. Kazban, F. Ferrante, and A. Chowdhury. "Drip Shield-Waste Package Mechanical Interaction." San Antonio, Texas: CNWRA. 2006.
‖ Bechtel SAIC Company, LLC. "Technical Basis Document No. 14: Low Probability Seismic Events." Rev. 1. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2004.

Second, the DOE waste package seismic analyses do not include the potential for drip shield collapse. Ibarra, et al. (2006) performed a simplified seismic evaluation of the drip shield–waste package interaction (Case 8 of Table 5-2) and suggested that the waste package safety margin may be significantly reduced for seismic events associated to a mean annual frequency of exceedance of 1×10^{-5} or lower, and for some realizations it may be less than unity. In this study, the failure mode refers to the strain associated to the ultimate tensile strength of the material and assumes that stress corrosion cracking and environmental conditions do not affect the material constitutive relationships. Note that DOE failure criterion is based on residual stress thresholds smaller than the yield stress of the material to prevent stress corrosion cracking (Bechtel SAIC Company, LLC, 2004g,h). Although this failure mode definition may be conservative for permanent loading conditions in which the stresses are not relieved, the CNWRA staff are concerned that using residual stresses to estimate damage may underestimate severe plastic deformation occurring during impact transient loading.

The waste package structural performance under seismic events requires further examination because the independent evaluation (Ibarra, et al., 2006) uses a simplified analysis. Although the DOE dynamic analyses are more refined, the seismic loading scenarios are different from those predicted by the staff. Therefore, the CNWRA staff are concerned that DOE has not evaluated an important failure mechanism that may affect the performance of a key barrier in its repository design concept.

5.2 Effects of Drift Degradation on Seepage and In-Drift Environment

This section discusses the potential effects of drift degradation on seepage and thermohydrological conditions within the drifts. Enhanced understanding of the in-drift thermohydrological processes in the emplacement drift and in the near-field environment is vital to determine the quantity and composition of pore water that may contact the waste package and to evaluate the potential for corrosion of waste packages.

5.2.1 Background

The thermohydrological process is conceptualized as a coupling of heat transfer and fluid movement. If the decay heat resulting from emplaced waste is sufficient to cause boiling, water can be vaporized and driven away from the vicinity of the drift (Figure 5-1). The return of moisture to the resulting dryout zone may take a long time, except by preferential flow of refluxed water along fractures that could breach the dryout zone. Extended periods of dryout could result in reduced risk of corrosion of waste packages and in limited movement of radionuclides in the natural environment until rewetting occurs. The extent and duration of the dryout zone are also dependent on the amount of water available from refluxing. Refluxing occurs when vapor encounters cooler portions of the rock away from the drifts, condenses, and increases the saturations in the fractures. While a portion of the condensate may be imbibed into the matrix, the condensate in the fractures can become mobile and flow toward the drift. In addition, temperature gradients may lead to the early presence of moisture (condensation, ambient percolation) in the drift. The presence, extent, and longevity of dryout zones and the presence of temperature gradients depend on the magnitude and distribution (spatial and temporal) of thermal loads and the percolation flux through the repository horizon. Other processes that could influence the in-drift conditions include preclosure forced ventilation and postclosure natural convection. Differences in the cooling rate of the waste packages because

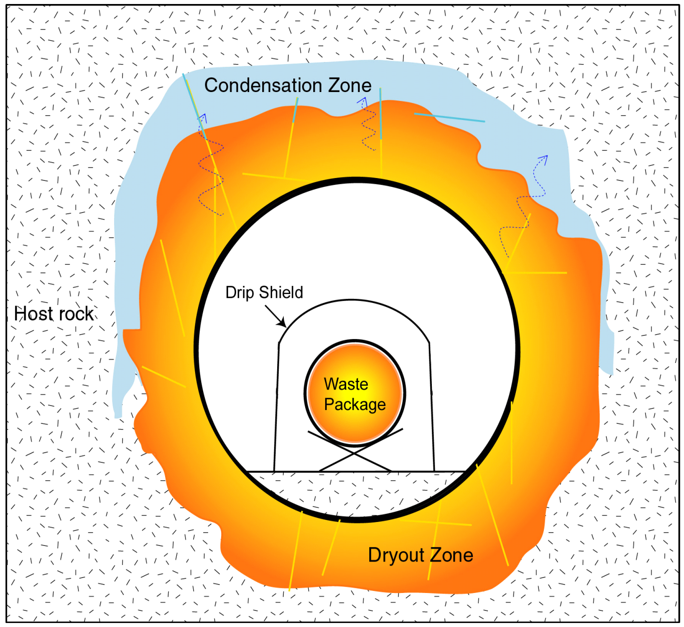

Figure 5-1. Schematic of the Thermohydrological Processes in the Near-Field Environment

of their proximity to the edge of the repository (i.e., the edge-cooling effect) and differences in individual waste package heat load (cold-trap effect) could cause temperature gradients in the drifts that may lead to faster wetting of the in-drift components.

The thermohydrological conditions are also dependent on the geometric configuration of various in-drift components. Previous work by Gute, et al. (2003) and Ibarra, et al. (2006) indicate that most of the drifts may be naturally backfilled by rockfall rubble early in the performance period. The thermal-mechanical response to the heat load imparted by the emplaced radioactive waste may lead to a natural backfill of coarse to fine rock blocks of varying shapes (Ofoegbu, et al., 2006). Depending on their geometric characteristics, the blocks likely will be poorly sorted. Thermal-mechanical results also provide approximations of the thickness of the rubble pile and drift degradation height, both as a function of time.

5.2.2 Influences of Rubble on In-Drift Heat Transfer

The in-drift heat transfer processes are dependent on the geometric configuration of the in-drift components. Detailed process models, described in Section 5.2.5, indicate that the presence of rubble leads to elevated waste package temperatures. Drift degradation will modify convective heat transfer and moisture movement along drifts relative to the case of an open drift. An additional complexity is that the degradation is likely to vary spatially along a drift. Nonuniform degradation could have a large effect on in-drift convective heat transfer and moisture redistribution and could create convection cells between degraded portions of drifts. The evolution of the in-drift temperatures is sensitive to the representation of the heat transfer processes in the rubble and the rate of drift degradation.

5.2.3 Influences of Rubble on Seepage

In-drift moisture movement is significantly affected by the rubble because heat loads, host rock thermohydrological properties, and degradation are expected to vary along the drift, and an edge-cooling effect may be experienced (Manepally and Fedors, 2003). In-drift heat transfer processes are dependent on the amount of rubble present, the air gap between the top of the rubble and the drift wall, and the interstitial space in the rubble pile. The location and amount of seepage that could contact the waste in a degraded drift depend on several factors.

- Dripping processes that depend on the shape and roughness of the degraded drift wall

- Film flow along the drift wall that could influence the drift shadow effect and enhance rates of advection and diffusion in the rock below drifts

- Convergence or divergence of flow in the rubble

- Degradation of the drip shield [i.e., if the drip shield fails (mechanical failure) then convection below the drip shield changes, which may allow water directly to contact the waste package; flow may be localized where drip shields fail because this is where the drift has degraded most]

- Effectiveness of the vapor barrier in the rubble (i.e., extent of preferential flow through high temperature gradients expected in regions of the rubble nearest the drip shield or waste package)

The factors affecting seepage in a degraded drift are dependent on the shape, size, and distribution of the rubble. There is lack of sufficient data and analysis to estimate the particle size distribution of the rubble.

5.2.4 DOE Models of Seepage and In-Drift Environment for a Degraded Drift

DOE seepage models represent flow in the unsaturated zone using single continuum models with strong capillarity influence and assume degradation occurs (i.e., a rubble pile forms) only under the seismic scenario. Partial or complete collapse of the drifts resulting from thermal effects, stresses related to excavation, or other mechanisms have been excluded because DOE argued they do not significantly affect long-term performance of the repository (Bechtel SAIC Company, LLC, 2004c).

Several experiments have evaluated seepage in intact drifts: (i) *in-situ* seepage injection tests in the niches and Enhanced Characterization of the Repository Block, (ii) passive tests in the Enhanced Characterization of the Repository Block, and (iii) evaluation of analog sites (Peña Blanca). There were no experiments, however, related to seepage into degraded drifts.

The effects of drift degradation on seepage rates have been considered for the current abstraction of drift seepage (Bechtel SAIC Company, LLC, 2003b, Section 6.4.2.4). In nonlithophysal host rock units, DOE expects small changes to the drift geometry from local breakout of key blocks (Bechtel SAIC Company, LLC, 2001). Seepage modeling results for the key block breakout scenario showed only a small effect on seepage rates, which is within the uncertainty of seepage estimates already included in the seepage abstraction (Bechtel SAIC Company, LLC, 2003c, Section 6.6.3). Different drift degradation modes for lithophysal units (Bechtel SAIC Company, LLC, 2003d) prompted DOE to also consider a drift degradation scenario in which the original drift opening is increased in size but is filled with fragmented rubble and large voids. DOE simulations indicate most of the percolation flux would still be diverted around the collapsed drift (the drift wall would remain circular and smooth), but seepage rates would be larger for the collapsed drift scenario because the drift footprint is assumed to approximately double in size, thereby doubling the amount of percolation flux arriving at the collapsed drift. Increased seepage entering a drift does not necessarily translate to increased water contacting waste packages, however, because the footprint of the waste package remains unchanged. The collapsed drift scenario is integrated into the seepage abstraction by using a lookup table for collapsed drift seepage estimates that considers the same ranges of capillary strength, mean fracture permeability, and percolation flux as in the basecase abstraction (NRC, 2005). The lookup table includes an enhancement factor of 20 percent in seepage due to thermal stress, rock strength degradation, or minor to moderate seismic events (Bechtel SAIC Company, LLC, 2004c).

Seepage change is included in the seismic abstractions by modifying the seepage flux in the lithophysal zones after a seismic event. This is attributable to an increased drift size, an altered drift shape, and the capillary strength that exists in the rubble in the drift. This change is invoked after a seismic event occurs, provided the ground motion is large enough to degrade the drifts. For nonlithophysal zones in the seismic scenario, the seepage abstraction follows the nominal scenario discussed above, which includes an enhancement factor for uncertainty in seepage due to partial collapse of drifts (Bechtel SAIC Company, LLC, 2004c).

In addition to switching to the seepage lookup table for collapsed drifts, a temperature constraint is also applied to the seepage flux after drift collapse in the lithophysal and nonlithophysal zones. Specifically, the seepage onto the waste package is set to zero for the period of above-boiling temperatures by using a 100 °C [212 °F] threshold temperature at the waste package surface. This constraint implies that seepage can enter the drift and be diverted through the rubble to the invert beneath the waste package but cannot contact the waste package surface until the waste package surface temperature drops below 100 °C [212 °F].

The influence of a low-probability collapsed-drift seismic scenario on in-drift thermal hydrologic conditions is considered in the Multiscale Thermohydrologic Model (Bechtel SAIC Company, LLC, 2004j, Section 6.3.7). Submodels that comprise the Multiscale Thermohydrologic Model are altered to simulate conditions that are predicted to exist after a seismic event that causes drift collapse. The model generates a list of changes to the location-specific temperature and relative humidity provided by the basecase. The collapsed-drift scenario implemented in the submodels considers a high and low case for the in-drift thermal conductivity, which correspond to a predicted range of thermal conductivity between the drip shield and the expanded drift boundaries (Bechtel SAIC Company, LLC, 2004j, Section 6.2.10). Changes in temperature and relative humidity have been estimated for eight different waste package emplacement configurations using high and low values of thermal conductivity for wet and dry rubble in the drifts. These results provide the basis for modifying the waste package temperature and relative humidity after a seismic event.

The DOE seepage model for degraded drifts assumes perfectly circular but larger openings compared to the nondegraded drift seepage model (Bechtel SAIC Company LLC, 2004k). Given the potential shapes for degraded drifts discussed in Section 4.2.4.1, a circular opening for a degraded drift does not appear realistic. To support the use of a circular, but larger, degraded drift opening, DOE presented results in Bechtel SAIC Company, LLC (2004l) from another model that showed seepage for noncircular openings was, on average, the same as for the original circular openings. In this second model, the drift radius remained constant, but the numerical mesh was modified to reflect chunks or blocks of fallen rock from the drift ceiling. The DOE model used stochastic realizations of fracture heterogeneity in the host rock. With blocks removed from the drift ceiling, many of the realizations led to smaller estimates of seepage for degraded drifts as compared to nondegraded drifts. On average, seepage was about the same for degraded and nondegraded drifts (Bechtel SAIC Company, LLC, 2004l). Theoretically, uneven topology of drift ceilings should lead to similar or more seepage as compared to smooth circular openings. Staff have not completed their analysis and evaluation of the DOE magnitude of change in seepage caused by drift degradation.

Drift seepage, one of the direct controls on the quantity of water contacting engineered barriers and waste forms, is potentially affected by the presence of rock bolts in the repository emplacement drifts. It is important to understand the DOE technical basis for excluding the effect of rock bolts in performance assessments. To evaluate the impact of rock bolts on hydrology and seepage, DOE developed a refined seepage model that includes rock bolts (Bechtel SAIC Company, LLC, 2003c, Section 6.5). Results from the DOE hydrologic model indicated the impact of rock bolts on seepage is negligible.

Staff may seek clarification during the license application review process regarding the effect of rock bolts on flow above the drift and on dripping from the drift wall (Kokajko, 2005). Rock bolts were modeled as open boreholes. Although the rock bolts will not be grouted, NRC believes they will directly contact the host rock. Therefore, the capillary barrier effect assumed for the rock bolt opening in the DOE rock bolt seepage model may lead to underestimates of seepage along rock bolts. Furthermore, the rock bolts will protrude from the drift wall and may serve as focal points for seepage water and condensate water dripping onto the engineered barrier system and invert. Under ambient conditions, enhanced seepage due to rock bolts would be less than during the thermally perturbed period (Kokajko, 2005). The rock bolts may serve as preferential flow pathways during this period. Water buildup in the reflux zone may preferentially flow down openings along rock bolts and drip onto the engineered barrier system and invert.

5.2.5 Staff Approach to Evaluate Potential Effects of Drift Degradation on Seepage and In-Drift Environment

The pore-scale seepage model of Or, et al. (2005) was developed to better understand flow in fractures and seepage into openings (Figure 5-2). This model conceptualizes the fracture and matrix as continua with disparate pore size distributions. The processes of film- and capillary-driven flows are combined with a geometrically tractable representation of the dual-continuum fractured rock with two disparate populations of matrix pores and fracture apertures. Similar to previous studies (e.g., Finsterle, et al., 2003), the Or, et al. (2005) model indicates a percolation threshold for onset of seepage. The analysis exhibited a steep increase in seepage with an increase in percolation flux that reflects the role of fracture film. Although this study did not specifically consider the degraded drift scenario, the results are relevant because the flow mechanisms at the driftwall–rubble interface are similar to the driftwall–air interface in an intact drift. This is attributed to the large difference in the capillary forces in the intact rock and the rubble. Future experimental and numerical models, described in the following sections, will examine flow mechanisms at the driftwall–rubble interface.

Staff also developed detailed process models of in-drift and near-field thermohydrological conditions for degraded and intact drift scenarios. These models are needed to estimate the composition of water that may contact the waste package and to evaluate the potential for corrosion of waste packages. In addition, they provide a basis for model abstractions used in performance assessment.

Fedors, et al. (2004a) evaluated the effect of rubble on the in-drift heat transfer processes. Their analysis indicated that if the drip shield remains intact below the rubble pile, convective heat transfer and moisture movement could occur beneath the drip shield and in the air pocket above the rubble pile. Convective heat transfer also may occur through the rubble pile.

Radiative heat transfer may also occur between rock fragments and is more likely to be an effective heat transfer mechanism if the fragments are large and poorly packed. Fedors, et al. (2004a) suggested that one of the consequences of nonuniform drift degradation related to convective heat transfer may be increases in the local temperature gradients. These may increase convective air and moisture transfer along the drift between waste packages or zones of waste packages. Furthermore, Fedors, et al. (2004a) noted that localized degradation may bound separate zones of axial convection, with the highest temperatures occurring where rubble piles cover drip shields.

Mohanty, et al. (2006) suggest a model that accounts for convective heat transfer through the natural backfill in addition to conductive heat transfer. The convective regime is determined from the air flow characteristics of the accumulated rubble material and derived from the rubble size distribution. Conduction and convection through the natural backfill would lower overall waste package surface temperature relative to conduction alone, but the process appears to be strongly controlled by the mean rubble diameter and void porosity. The rubble size distribution determines the regime over which convective heat transfer may be the dominant heat transfer mechanism; different rubble size distributions may produce heat transfer ranging from pure conduction dominated to convection dominated. Convection will dominate only when the porosities are high and the temperature gradient is large, which may be the case during the early period when the temperature peaks.

Green, et al. (2004) investigated important heat and mass transfer mechanisms under the expected range of thermal conditions. The objective was to measure heat transfer through samples of the Topopah Spring lower lithophysal unit at Yucca Mountain as an analog to the rubble. A bulk (effective) thermal conductivity value of 0.4 W/m-K [0.2 BTU/h-ft-F] was derived from measurements made at low temperatures, low thermal gradients, and low saturation under steady-state conditions. Empirical relations developed by Green, et al. (2004) for the granular packed bed media with a maximum particle diameter of 6 cm [2.4 in] suggest that even at elevated temperatures heat transfer by radiation was negligible. A radiative heat transfer model combined with a conduction model could also have been used to match the laboratory data. Convection, inferred to be that portion of heat transfer not attributed to conduction and radiation, was observed in the experiments at temperature gradients in excess of 600 °C/m [330 °F/ft].

Manepally, et al. (2004) developed a two-dimensional detailed process model that incorporates

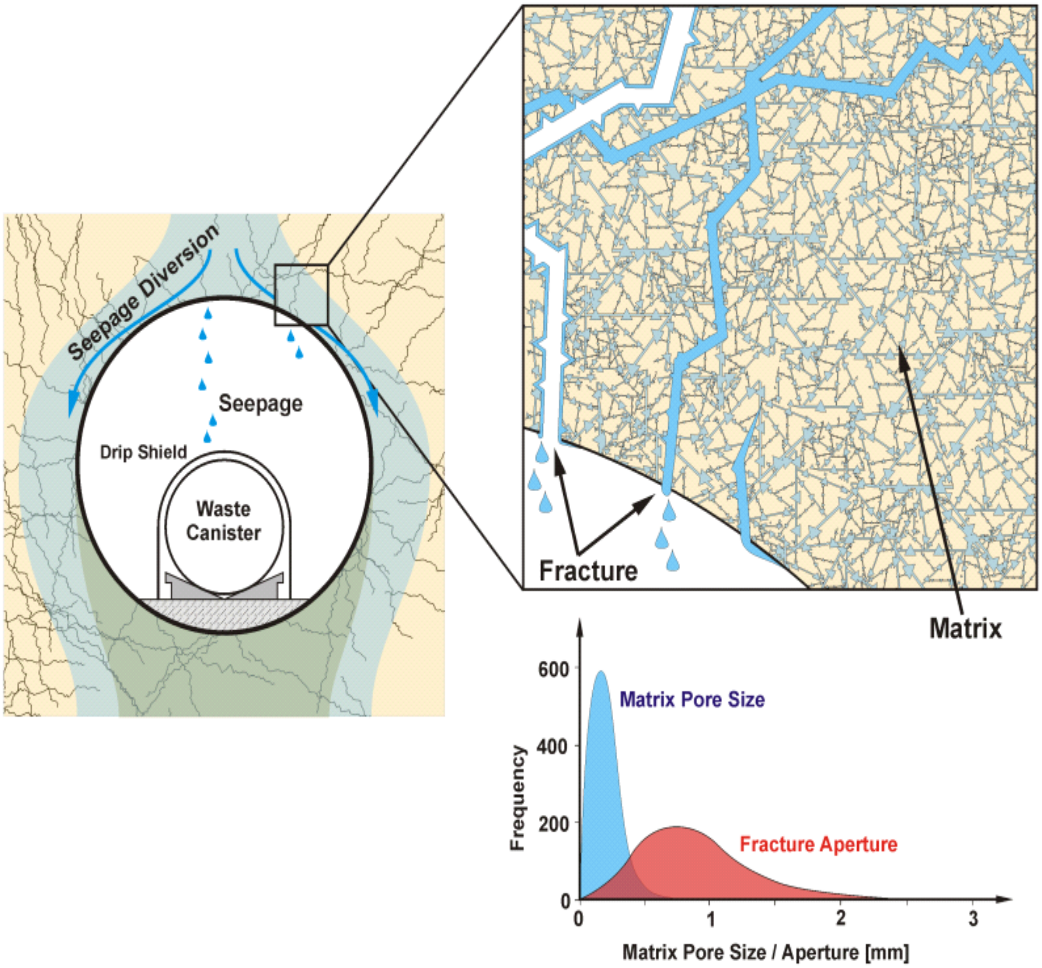

Figure 5-2. Conceptual Sketch of a Fractured Porous Medium. Fractures May Be Represented by Unit Elements as Depicted in the Right Upper Corner, and Matrix Is Represented by Angular Pores Connected to Slits. Note (a) the Pore Size Disparity Between the Two Domains, and (b) Large Fractures Empty First (Or, et al., 2005).

the temporal variation of in-drift and drift wall geometry (Figure 5-3). Rubble around the waste packages and drip shields will elevate the temperatures of the waste packages. Model results indicate that thermal radiation and convection dominate in-drift heat transfer until the drip shield is completely surrounded by rubble. Subsequently, the insulating effect of rubble causes an abrupt increase in the temperatures of the in-drift components, and conduction through the rubble dominates the in-drift heat transfer (Figure 5-4). The heat generated by emplaced waste drives water away from the drift, creating a dryout zone and redistributing pore fluids within a potentially large volume of host rock. Water seepage into the drift is strongly affected by the extent and duration of the dryout zone. Model results show the temporal variability of the dryout zone, both in the host rock and the rubble pile. Heat transfer in the host rock is relatively less affected by drift degradation because conduction dominates heat transfer in the intact host rock.

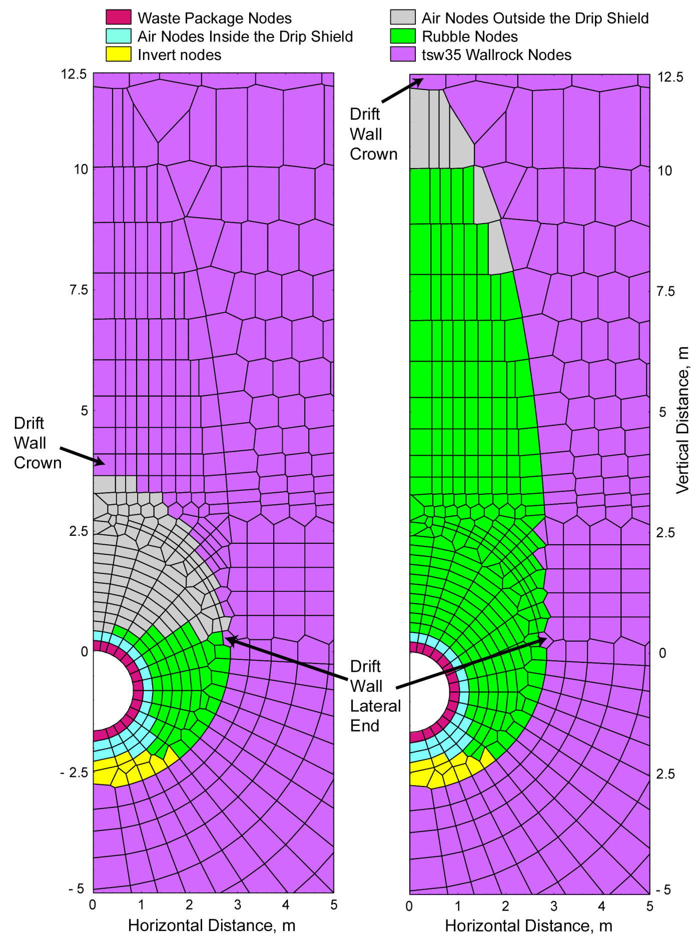

Figure 5-3. Example of Nodal Assignments for Two Different Periods: (a) 130–160 Years and (b) 790–10,000 Years in the Detailed Process Thermohydrological Model (Manepally, et al., 2004)

Sensitivity analyses show that the in-drift thermohydrologic conditions are sensitive to the thermal properties of the rubble and the rate of drift degradation.

5.2.6 Chemical Environment in the Degraded Drift

The current proposed model for the NRC Total-system Performance Assessment code assumes chemical equilibrium for all scenarios, so the chemistry of seepage water contacting the drip shield–waste package is the same for the degraded and nondegraded drift scenarios. Under both scenarios, seepage water would contact the repository rock units either at the intact drift wall or the rubble on the drip shield or waste package. Interaction of seepage water and

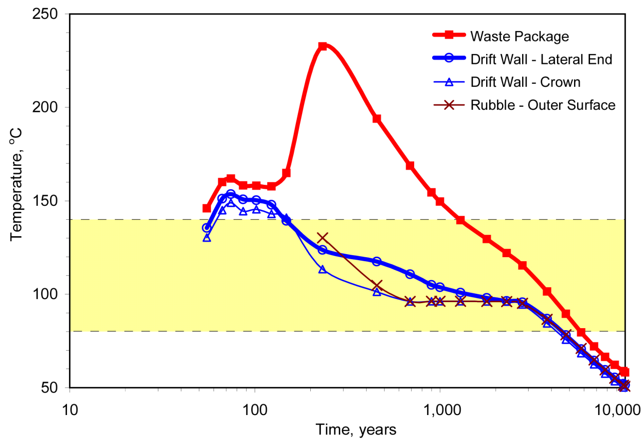

Figure 5-4. Temperature Estimates at Various Locations [°F = (1.8 × T °C + 32)]. (Shaded Region Denotes Susceptibility Window for Localized Corrosion of the Waste Package.) (Manepally,et al., 2004)

rock in the vicinity of the heated drift is controlled by the above-boiling temperature of the rock. Under the elevated temperature conditions in a degraded drift, seepage water could drip from the drift wall onto the rubble and evaporate before entering the elevated temperature region near the drip shield waste package interface. Once the temperature of the rubble decreases sufficiently, seepage water could migrate through the rubble and contact the drip shield or the waste package.

6 REPRESENTATION OF DRIFT DEGRADATION IN PERFORMANCE ASSESSMENT

This chapter discusses the DOE approach for representing the effects of drift degradation in the Total System Performance Assessment model. A proposed independent abstraction to help staff understand the effects of drift degradation on repository performance is also discussed.

6.1 DOE Representation

As noted in Chapter 2, many features, events, and processes related to drift degradation are excluded from consideration in the DOE performance assessment model on the basis of low consequence on the performance of the repository system. The only exception is the effect of drift degradation on in-drift thermohydrology, which DOE considers for low-probability seismic events. For this case, DOE abstracts the process into the performance assessment model via lookup tables populated using process-level analyses (Chapter 2).

The annual frequency of exceedance and time of the seismic events considered for the evaluation of drift degradation effects on in-drift thermohydrology are sampled parameters (Bechtel SAIC Company, LLC, 2004g). The annual frequency of exceedance is sampled from a log-uniform distribution ranging from 10^{-4} yr^{-1} to 10^{-8} yr^{-1}. The seismic motion peak ground velocity is defined as a function of the annual frequency of exceedance (Bechtel SAIC Company, LLC, 2004g). The time of the event is sampled from a log-uniform distribution ranging from 10 years to the end of the simulation period. DOE assumes that drifts in the lithophysal rock units collapse for events with ground motions greater than 0.384 m/s [1.26 ft/s] and that nonlithophysal units do not collapse, even for large seismic events. However, some marginal rockfall may occur in the nonlithophysal rock units.

Seepage into the emplacement drifts is modeled via lookup tables derived using the Multiscale Thermohydrologic Model (Bechtel SAIC Company, LLC, 2004j). The amount of seepage entering the drift is computed as a function of the occurrence of drift degradation. Nonlithophysal or moderately degraded drifts (Bechtel SAIC Company, LLC, 2004k). Lithophysal rock units are estimated to remain largely intact for the nominal scenario and less severe seismic events (Bechtel SAIC Company, LLC, 2004b), where the seepage model in lithophysal rock units is similar to the nonlithophysal zones model (Bechtel SAIC Company, LLC, 2004g,k). For seismic events with an annual probability of exceedance below 10^{-4} yr^{-1}, however, emplacement drifts in lithophysal rock units are assumed to collapse (Bechtel SAIC Company, LLC, 2004b), increasing seepage rates (Bechtel SAIC Company, LLC, 2004f,j,l). One factor potentially causing this increase in seepage is widening of the emplacement drift (Bechtel SAIC Company, LLC, 2004l). In the performance assessment model for low-probability seismic events, the collapsed drift seepage rate is selected for the entire simulation time (Bechtel SAIC Company, LLC, 2004k).

DOE does not currently include potential effects of drift degradation on temperature and relative humidity for drifts in nonlithophysal rock units because these are argued not to collapse and generate only marginal volumes of detached rock (Bechtel SAIC Company, LLC, 2004f). On the other hand, the temperature and relative humidity in lithophysal rock units are adjusted for the low-probability seismic events to account for the effects of drift collapse, based on lookup tables derived using the Mulitscale Thermohydrologic Model (Bechtel SAIC Company, LLC, 2004j).

6.2 Proposed NRC Representation of Drift Degradation in Performance Assessment

This section summarizes the proposed drift degradation abstraction for the NRC Total-system Performance Assessment (TPA) model. The models supporting the Total-system Performance Assessment have been described elsewhere. Only pertinent details of the drift degradation scenario abstraction are presented in this section, with references to sources with additional details. In previous chapters, concerns with the information supporting the DOE analysis of drift stability and its potential effects on repository performance have been identified. The abstracted models discussed in this chapter are aimed at enhancing staff understanding of potential consequences of drift degradation processes on repository performance.

6.2.1 Proposed NRC Abstraction of Drift Degradation

Based on the CNWRA estimates of thermal stresses in the drifts following permanent closure, rubble spallation from the drift wall is assumed to occur at a constant rate, calculated from the bulking factor and the time required to fill the drift with rubble. Rubble is assumed to fill a geometry of either a chimney or trapezoidal configuration, based on the DOE distribution of rock strength categories (Ibarra, et al., 2006). As described by Ibarra, et al. (2006), seismic events could compact the accumulated rubble, creating additional void volume that may allow additional spalling of rock. A maximum recurrence rate of 10^{-4} yr^{-1} is assumed to define the timing of seismic events, with a randomly sampled magnitude (mean annual probability of exceedence).

6.2.2 Proposed NRC Abstraction of Engineered Barrier System Response to Drift Degradation

Potential consequences of drift degradation are considered to assess impacts on total system performance. The consequences considered include effects of temperature, seepage, drip shield collapse, mechanical interactions of the drip shield with the waste package, and localized corrosion of waste packages contacted by seepage waters flowing through rubble.

The drift wall temperature is estimated using a continuum repository-scale model described elsewhere (Mohanty, et al., 2002; Fedors, et al., 2004b). A simplified thermal network is used to compute waste package and drip shield temperatures as a function of the drift wall temperature and the thermal load (Fedors, et al., 2004b). Degradation of the drifts could cause the drift wall to recede from the waste packages, thereby potentially decreasing the drift wall temperature. On the other hand, the accumulated rubble may insulate the waste packages and drip shields, thereby potentially increasing their temperatures. In the proposed abstraction, the drip shield temperature is assumed to define the onset of seepage water to bypass the accumulated rubble. This seepage could contact the waste package if the capability of the drip shield to divert water is compromised. Waste package temperatures are used to estimate waste form dissolution rates if water contacts the waste forms.

The proposed abstraction to independently evaluate the effect of drift degradation on the structural stability of the drip shields is described in Ibarra, et al. (2006). In the model, the accumulated rubble loads calculated from the bulking factor and collapsed configuration (i.e., chimney or trapezoidal) are compared to a structural capacity of the drip shield. Drip shield collapse is assumed if the accumulated rubble loads exceed the structural capacity of the drip shield. The model considers dynamic amplification of loads due to seismic ground motions. If collapsed, the ability of the drip shield to divert water could be compromised. Initially, the abstraction assumes that collapsed drip shields are capable of diverting some of the incoming seepage. Over time the capability of the drip shield to divert seepage diminishes at a constant rate until the drip shield is fully corroded, at which time no further water diversion is considered.

If the drip shield collapses, then seepage water may contact the waste package during the thermal period, possibly leading to the formation of evaporative brines on the waste package and inducing localized corrosion. Detailed descriptions of the proposed evaporative brine chemistry and localized corrosion abstractions have been provided by Dunn, et al. (2005) and Pensado, et al. (2006). Based on numerical simulations of evaporation of waters present in the repository host rock in the unsaturated zone, pH and concentrations of ionic species in potential brines were estimated. Localized corrosion could initiate if the Alloy 22 corrosion potential exceeds the repassivation potential (both potentials are computed as functions of the ionic concentrations, temperature, and pH). If the drip shield fails to divert water only after the thermal period, the waste package temperature may not be sufficient to support localized corrosion.

A collapsed drip shield may transfer accumulated rubble loads to the waste package, possibly resulting in mechanical breaching of the waste package. Details of the proposed abstraction are described in Ibarra, et al. (2006), which focused on the transfer of rubble loads through drip shield bulkheads and longitudinal stiffeners. Similar to the drip shield collapse abstraction, the transferred accumulated rubble load is compared to the structural capacity of the waste package. When the demand exceeds the capacity, waste package breaching is assumed to occur. The abstraction also considers amplification of static loads from seismic events. Once the drip shield plates are fully corroded, accumulated rubble loads are assumed redistributed over a wider area than bulkheads and stiffeners. Load redistribution is assumed sufficient to lower the demand below the waste package capacity. Therefore, mechanical breaching of the waste packages could occur until the drip shield plates are fully corroded, and not at all afterward. Similar to the drip shield collapse abstraction, the model implements an initial breaching fraction on the waste package surface, which may grow at an assumed constant rate (e.g., later seismic events may cause the breached area to grow) until waste package materials are completely corroded, after which no further water diversion by the waste package is considered.

7 SUMMARY AND RECOMMENDATIONS

The current staff understanding of drift degradation at a potential Yucca Mountain repository and its possible effects on repository performance are summarized in this report. Independent analyses show that potential degradation of the emplacement drifts after permanent closure likely affects the mechanical integrity of engineered barriers and thermohydrologic parameters important to corrosion and seepage. These effects appear potentially important to waste isolation, depending on the extent, timing, and rate of drift degradation. This report examines DOE information characterizing the degradation of emplacement drifts after permanent closure. DOE use of the information to support disposition of features, events, and processes related to drift degradation also was examined. The report focused on understanding the DOE information, staff views of the information, and independent CNWRA staff analyses relevant to the information. The use of drift degradation information in performance assessments was discussed, considering the DOE approach and the staff independent performance assessment. Staff questions regarding uncertainties in DOE information for drift degradation and potential effects on repository performance are highlighted. The following observations arise from information presented in the report.

DOE analysis indicates significant drift degradation may result from low probability seismic events, but the effects of repository thermal loading and time-dependent rock weakening on drift degradation would be insignificant for 10,000 years. Therefore, the DOE performance assessment (i) does not intend to include any effects of drift degradation in the basecase (or nominal) scenario, (ii) would include the effects of rubble accumulation in the analysis of seepage and thermohydrologic parameters for the seismic scenario, and (iii) would exclude accumulated-rubble loading from the seismic scenario because DOE intends to design the drip shield to withstand such loading. Consequently, DOE performance assessment does not intend to consider potential drip shield mechanical collapse in assessing the integrity of drip shields and waste packages.

Based on current staff understanding, the apparent DOE approach to accounting for the potential effects of drift degradation in Total System Performance Assessment does not include a complete range of credible failure modes for the engineered barriers. Independent analyses by the Center for Nuclear Waste Regulatory Analyses (CNWRA) suggest (i) repository thermal loading (based on current DOE design concept) alone could cause degradation of the emplacement drifts and significant accumulations of rock rubble within approximately 1,000 years after closure and (ii) the drip shield, as currently designed, could collapse onto the waste package as a result of static or seismic loading and creep from the accumulated rock rubble. Staff currently are evaluating the risk significance of these results in the NRC Total-system Performance Assessment. The central concern, however, is that potentially significant failure modes of the engineered barriers are not being appropriately considered by DOE. For example, analysis of the current drip shield design indicates that an assessment of the mechanical performance of the waste package would need to consider a range of potential loading from a collapsed drip shield. Independent CNWRA analyses suggest mechanical breaching of the waste package under static loading conditions appears unlikely, but the effects of seismic loading warrant additional consideration. A first-order CNWRA analysis of loading during seismic events at a mean annual frequency of exceedance of 1×10^{-5} per year or lower indicates the waste package safety margin against mechanical failure may be significantly reduced, and for some realizations it may be less than unity. Additional analyses are warranted to understand how potential static or seismic loading may affect the mechanical integrity of a waste package subjected to loading from a collapsed drip shield. The current DOE approach, however, does not consider a complete range of loading conditions and processes such as creep that may affect the performance of the drip shield or waste package, and DOE has not planned to conduct additional analyses in these relevant areas.

Staff raised several questions during DOE and NRC technical exchanges and management meetings to address uncertainties in DOE information for drift degradation and its potential effects on repository performance. To address the staff questions, DOE performed laboratory and field tests and analyses using several different numerical modeling techniques. The DOE testing and analyses still showed appreciable uncertainties regarding drift degradation processes. These uncertainties were resolved by a DOE commitment to develop a drip shield design that would be structurally competent to withstand the effects of drift degradation. Staff relied on this commitment in recommending closure of several key technical issue agreements related to drift degradation, mechanical performance of the drip shield, and the effects of drift degradation on seepage and thermohydrologic near-field parameters.[1,2] Available information, however, indicates that the current DOE drip shield design apparently does not accomplish the DOE-established design objective in response to the full range of loadings associated with drift degradation processes.

The presence or absence of an intact drip shield affects the performance of the engineered barrier system, with the most sensitive effects likely occurring during the thermal period of postclosure. Thus, an understanding of drip shield performance appears necessary for developing a complete understanding of the total system performance of the potential repository system. Based on their evaluations, staff recommend an interaction with DOE to discuss the mechanical performance of the drip shield design. This interaction would include discussion of the drift degradation parameters used to assess drip shield performance and the approaches used to assess the mechanical performance of waste packages in the event of drip shield collapse for both nominal and seismic scenarios.

DOE also needs to clarify the duration of ventilation during the preclosure period. Current DOE analyses indicate the emplacement drifts and other underground openings would be stable for 50 years after waste emplacement, if the drift thermal load is reduced by 90 percent through active ventilation of the emplacement drifts. DOE should clarify whether active ventilation would continue if the preclosure period should extend beyond 50 years. Alternatively, DOE could provide information to assess the stability of the underground openings under a full thermal load (i.e., if not ventilated). Stability of underground openings through the preclosure period appears relevant to staff reviews of a potential license application in areas including performance confirmation, implementation of design assumptions used in performance assessment, and aspects of repository operations before permanent closure.

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[1]Pre-licensing Evaluation of Agreements in “Technical Basis Document Number 4, Mechanical Degradation and Seismic Effects” and Three Other Associated Agreements. Letter, January 11: L.E. Kokajko (NRC) to J.D. Ziegler (DOE). 2005.
[2]"Pre-licensing Evaluation of Container Life and Source Term Agreements CLST.1.14, 2.08 and 2.09 in Technical Basis Document Number 6, Waste Package and Drip Shield Corrosion.” Letter, December 29: L.E. Kokajko (NRC) to J.D. Ziegler (DOE). 2004.

8 REFERENCES

ABAQUS, Inc. “ABAQUS User’s Manual.” Version 6.5. Providence, Rhode Island: ABAQUS, Inc. 2004.

Ahola, M.P. “A Parametric Study of Drift Stability in Jointed Rock Mass Phase II: Discrete Element Dynamic Analysis of Unbackfilled Drifts.” CNWRA 97–007. San Antonio, Texas: CNWRA. 1997.

Ahola, M.P and A.H. Chowdhury. “Effect of Seismic Load on a Proposed Nuclear Waste Repository at Yucca Mountain.” *International Journal of Rock Mechanics and Mining Science*. Vol. 34, No. 3-4. Paper No. 007. 1997.

Albin, A.L., W.L. Singleton, T.C. Moyer, A.C. Lee, R.C. Lung, G.L.W. Eatman, and D.L. Barr. “Geology of the Main Drift—Station 28 + 00 to 55 + 00, Exploratory Studies Facility, Yucca Mountain Project, Yucca Mountain, Nevada.” DOE Report DTN GS970208314224.005, Milestone Report SPG42AM3. Denver, Colorado: Bureau of Reclamation and U.S. Geological Survey. 1997.

Ankem, S. and T. Wilt. “A Literature Review of Low Temperature (<0.25Tm) Creep Behavior of a, a-b and b Titanium Alloys.” San Antonio, Texas: CNWRA. 2006.

Barr, D.L., T.C. Moyer, W.L. Singleton, A.L. Albin, R.C. Lung, A.C. Lee, S.C. Beason, and G.L.W. Eatman. “Geology of the North Ramp—Station 4+00 to 28+00, Exploratory Studies Facility, Yucca Mountain Project, Yucca Mountain, Nevada.” DOE Report DTN GS960908314224.020. Denver, Colorado: Bureau of Reclamation and U.S. Geological Survey. 1996.

Beason, S.C., G.A. Turlington, R.C. Lung, G.L.W. Eatman, D. Ryter, and D.L. Barr. “Geology of the North Ramp—Station 0+60 to 4+00, Exploratory Studies Facility, Yucca Mountain Project, Yucca Mountain, Nevada.” Denver, Colorado: Bureau of Reclamation and U.S. Geological Survey. 1996.

Bechtel SAIC Company, LLC. “EBS Radionuclide Transport Abstraction.” ANL–WIS–PA–000001. Rev. 1. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2004a.

———. “Drift Degradation Analysis.” ANL–EBS–MD–000027. Rev 03. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2004b.

———. “Engineered Barrier System Features, Events, and Processes.” ANL–WIS–PA–000002. Rev 03. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2004c.

———. “Development of Earthquake Ground Motion Input for Preclosure Seismic Design and Postclosure Performance Assessment of a Geologic Repository at Yucca Mountain, Nevada.” MDL–MGR–GS–000003. Rev. 01. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2004d.

———. “FEPs Screening of Processes and Issues in Drip Shield and Waste Package Degradation.” ANL–EBS–PA–000002. Rev. 03. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2004e.

———. “Drip Shield Structural Response to Rockfall.” 000–00C–SSE0–00300–000–00A. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2004f.

———. “Seismic Consequence Abstraction.” MDL–WIS–PA–000003. Rev. 01. Las Vegas, Nevada: Bechtel SAIC Company, LLC. ENG.20030327.0001. 2004g.

———. “Technical Basis Document No. 14: Low Probability Seismic Events.” Rev. 1. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2004h.

———. “Mechanical Assessment of the Drip Shield Subject to Vibratory Ground Motion and Dynamic and Static Rock Loading.” CAL–WIS–AC–000002. Rev. 00A. Las Vegas, Nevada: Bechtel SAIC Company. LLC. 2004i.

———. “Multiscale Thermohydrologic Model.” ANL–EBS–MD–000049. Rev. 02. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2004j.

———. “Abstraction of Drift Seepage.” MDL–NBS–HS–000019. Rev. 1. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2004k.

———. “Seepage Model for PA Including Drift Collapse.” MDL–NBS–HS–000002. Rev. 3. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2004l.

———. “Underground Layout Configuration.” 800–P0C–MGR0–00100–000–00E. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2003a.

———. “Abstraction of Drift Seepage.” MDL–NBS–HS–000019. Rev. 01. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2003b.

———. “Seepage Model for PA Including Drift Collapse.” MDL–NBS–HS–000002. Rev. 02. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2003c.

———. “Drift Degradation Analysis.” ANL–EBS–MD–000027. Rev. 02. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2003d.

———. “Geologic Framework Model (GFM2000).” Rev. 01. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2002.

———. “Drift Degradation Analysis.” AN–EBS–MD–000027. Rev. 1 ICN 01. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2001.

Cho, N., C.D. Martin, D.C. Sego, and R. Christiansson. “Modeling Dilation in Brittle Rocks.” *Rock Mechanics Across Borders and Disciplines*. Proceedings of the 6th North American Rock Mechanics Symposium, Houston, Texas, June 5–10, 2004. D.P. Yale, S.M. Willson, and A.S. About-Sayed, eds. ARM/NARMS Paper 04-483. Alexandria, Virginia: American Rock Mechanics Association. 2004.

DOE. “Repository Design Status.” Presentation (January 20) by P. Harrington (DOE, Office of Repository Development) to Nuclear Waste Technical Review Board. Las Vegas, Nevada: DOE, Office of Civilian Radioactive Waste Management. 2004a.

———. “Subsurface Facilities Design and Operations.” Presentation at the DOE/NRC Technical Exchange on Yucca Mountain Surface and Subsurface Facilities, September 14–15, 2004. Las Vegas, Nevada: DOE, Office of Civilian Radioactive Waste Management. 2004b.

Dunn, D.S., O. Pensado, Y.-M. Pan, R.T. Pabalan, L. Yang, X. He, and K.T. Chiang. “Passive and Localized Corrosion of Alloy 22—Modeling and Experiments.” CNWRA 2005–02. Rev. 1. San Antonio, Texas: CNWRA. 2005.

Eatman, G.L.W., W.L. Singleton, T.C. Moyer, D.L. Barr, A.L. Albin, R.C. Lung, and S.C Beason. “Geology of the South Ramp—Station 55+00 to 78+77, Exploratory Studies Facility, Yucca Mountain Project, Yucca Mountain, Nevada.” Denver, Colorado: Bureau of Reclamation and U.S. Geological Survey. 1997.

Fedors, R., S. Green, D. Walter, D. Farrell, S. Svedeman, F. Dodge, and R. Hart. “Environmental Conditions in Drifts.” San Antonio, Texas: CNWRA. 2004a.

Fedors, R., S. Green, D. Walter, G. Adams, D. Farrell, S. Svedeman. “Temperature and Relative Humidity Along Heated Drifts with and without Drift Degradation.” CNWRA 2004-04. San Antonio, Texas: CNWRA. 2004b.

Finsterle, S., C.F. Ahlers, R.C. Trautz, and P.J. Cook. “Inverse and predictive modeling of seepage into underground openings.” *Journal of Contaminant Hydrology.* Vols. 62–63. pp. 89–109. 2003.

Ghosh, A., S.M. Hsiung, and A.H. Chowdhury. “Seismic Response of Rock Joints and Jointed Rock Mass.” CNWRA 95–013. San Antonio, Texas: CNWRA. 1995.

Golder Associates, Inc. “FracWorksXP Module User Documentation.” Seattle, Washington: Golder Associates, Inc. 2002.

Golder Associates, Inc. “FracMan Interactive Discrete Feature Data Analysis, Geometric Modeling, and Exploration Simulation User Documentation.” Version 2.6. Seattle, Washington: Golder Associates, Inc. 1998.

Goodman, R.E. “Introduction to Rock Mechanics.” New York City, New York: John Wiley & Sons. 1980.

Green, R., J. Pohle, and J. Prikryl. “Heat Transfer through Rockfall.” *EOS Transactions of the American Geophysical Union*. Vol. 85, No. 47. Fall Meeting Supplement. Abstract H22B–04. 2004.

Gute, G.D., G. Ofoegbu, F. Thomassy, S. Hsiung, G. Adams, A. Ghosh, B. Dasgupta, A.H. Chowdhury, and S. Mohanty. “MECHFAIL: A Total-System Performance Assessment Code Module for Evaluating Engineered Barrier Performance Under Mechanical Loading Conditions.” CNWRA 2003–06. San Antonio, Texas: CNWRA. 2003.

Ibarra, L., T. Wilt, G. Ofoegbu, R. Kazban, F. Ferrante, and A. Chowdhury. “Drip Shield-Waste Package Mechanical Interaction.” San Antonio, Texas: CNWRA. 2006.

Ibarra, L., T. Wilt, G. Ofoegbu, and A. Chowdhury. “Structural Performance of Drip Shield Subjected to Static and Dynamic Loading.” San Antonio, Texas: CNWRA. 2005.

International Society for Rock Mechanics Commission on Testing Methods. “Rock Characterization Testing and Monitoring.” E.T. Brown, ed. Oxford, England: Pergamon Press. 1981.

Itasca Consulting Group, Inc. “UDEC Version 4.0, Universal Distinct Element Code. Theory and Background.” Minneapolis, Minnesota: Itasca Consulting Group, Inc. 2004.

Jaeger, J.C. and N.G.W. Cook. “Fundamentals of Rock Mechanics.” 3rd Edition. London, England: Chapman and Hall. 1979.

Kana, D.D., D.J. Fox, S.M. Hsiung, and A.H. Chowdhury. “An Experimental Scale-Model Study of Seismic Response of an Underground Opening in Jointed Rock Mass.” CNWRA 95–012. San Antonio, Texas: CNWRA. 1995.

Kana, D.D., B.H.G. Brady, B.W. Vanzant, and P.K. Nair. NUREG/CR–5440, “Critical Assessment of Seismic and Geomechanics Literature Related to a High-Level Nuclear Waste Underground Repository.” Washington, DC: NRC. 1991.

Kemeny, J., M. Apted, and D. Martin. “Rockfall at Yucca Mountain due to Thermal, Seismic and Time-Dependence.” *Global Progress Toward Safe Disposal*. Proceedings of the 11th International High-Level Radioactive Waste Management Conference, Las Vegas, Nevada, April 30–May 4, 2006. La Grange Park, Illinois: American Nuclear Society. 2006.

Kokajko, L.E. “Pre-Licensing Evaluation of Key Technical Issues Agreements: Total-System Performance Assessment and Integration 3.07 and General 1.01, Comments 13 and 95.” Letter (April 5) to J.D. Ziegler, DOE. ML050540056. Las Vegas, Nevada: NRC. 2005.

Lajtai, E.Z. and R.H. Schmidtke. “Delayed Failure in Rock Loaded in Uniaxial Compression.” *Rock Mechanics and Rock Engineering*. Vol. 19. pp. 11–25. 1986.

Manepally, C., A. Sun, R. Fedors, and D. Farrell. “Drift-Scale Thermohydrological Process Modeling—In-Drift Heat Transfer and Drift Degradation.” CNWRA 2004–5. San Antonio, Texas: CNWRA. 2004.

Manepally, C. and R.W. Fedors. “Edge-Cooling Effect on the Potential Thermohydrologic Conditions at Yucca Mountain.” Proceedings of the 10th International High-Level Radioactive Waste Management Conference, Las Vegas, Nevada, March 30–April 3, 2003. La Grange Park, Illinois: American Nuclear Society. Published on CD-ROM. 2003.

Mohanty, S.M., A. Ghosh, and G. Adams. “Heat Transfer by Natural Convection Through Rubble Generated by Drift Degradation.” Proceedings of the 11th International High Level Radioactive Waste, Las Vegas, Nevada, April 30–May 4, 2006. La Grange Park, Illinois: American Nuclear Society. 2006.

Mohanty S., T.J. McCartin, and D.W. Esh, coordinators. “Total-system Performance Assessment (TPA) Version 4.0 Code: Module Descriptions and User’s Guide.”

San Antonio, Texas: CNWRA. 2002.

Mongano, G.S., W.L. Singleton, T.C. Moyer, S.C. Beason, G.L.W. Eatman, A.L. Albin, and R.C. Lung. "Geology of the ECRB Cross-Drift—Exploratory Studies Facility, Yucca Mountain Project, Yucca Mountain, Nevada." SPG42GM3. Denver, Colorado: U.S. Geological Survey. 1999.

NRC. NUREG–1762, "Integrated Issue Resolution Status Report." Washington, DC: NRC. April 2005.

———. "U.S. Nuclear Regulatory Commission Staff Evaluation of U.S. Department of Energy Analysis Model Reports, Process Controls, and Corrective Actions." Washington, DC: U.S. Nuclear Regulatory Commission. 2004.

Ofoegbu, G.I. "Hydrological Implications of Thermally Induced Geomechanical Response at Yucca Mountain, Nevada." *Rock Mechanics in the National Interest*. Proceedings of the 38th U.S. Rock Mechanics Symposium, Washington, DC, July 7–10, 2001. Lisse, The Netherlands: A.A. Balkema Publishers. 2001.

Ofoegbu, G.I., B. Dasgupta, and K.J. Smart. "Assessing Effects of Thermal Loading on the Stability of Emplacement Drifts." *Global Progress Toward Safe Disposal*. Proceedings of the 11th International High-Level Radioactive Waste Management Conference, Las Vegas, Nevada, April 30–May 4, 2006. La Grange Park, Illinois: American Nuclear Society. 2006.

———. "Thermally Induced Rock Stress and Implications for Degradation of Emplacement Drifts at the Potential Yucca Mountain Nuclear Waste Repository—Letter Report." San Antonio, Texas: CNWRA. 2004.

Or, D., M. Tuller, and R. Fedors. "Seepage Into Drifts and Tunnels in Unsaturated Rock." *Water Resources Research*. Vol. 41, No. 5. 2005.

Owen, G.N. and R.E. Scholl. "Earthquake Engineering of Large Underground Structures." FHWA/RD-80/195. Washington, DC: Federal Highway Administration. 1981.

Pensado, O., R. Pabalan, D. Dunn, and K.-T. Chiang. "Use of Alloy-22 as a Long-Term Radioactive Waste Containment Material. Passivation of Metals and Semiconductors, and Properties of Thin Oxide Layer." A Selection of Papers from the 9th International Symposium, Paris, France, June 27–July 1, 2005. Phillippe Marcus and Vincent Maurice, eds. pp. 53–57. The Netherlands: Elsevier. 2006.

Sevougian, S.D. “Nominal and Seismic Scenarios.” *Presentation to DOE/NRC Technical Exchange on Total System Performance Assessment (TSPA) for Yucca Mountain*, *Sandia National Laboratories, October 24, 2006.* Las Vegas, Nevada. 2006.

Smart, K.J., D.Y. Wyrick, P.S. Landis, and D.J. Waiting. “Summary and Analysis of Subsurface Fracture Data from the Topopah Spring Tuff Upper Lithophysal, Middle Nonlithophysal, Lower Lithophysal, and Lower Nonlithophysal Zones at Yucca Mountain, Nevada.” CNWRA 2005–04. San Antonio, Texas: CNWRA. 2006.

Virgilio, M.J. “U.S. Nuclear Regulatory Commission Staff Evaluation of U.S. Department of Energy Analysis Model Reports, Process Controls, and Corrective Actions.” Letter (April 10) to M. Chu, DOE. Washington, DC: NRC. 2004.

Yang, L. “Corrosion of Alloy 22 in Concentrated Nitrate and Chloride Salt Environments at Elevated Temperatures—Progress Report.” CNWRA 2006–02. San Antonio, Texas: CNWRA. 2006.